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(71) Applicant: TOYOTA JIDOSHA KABUSHIKI KAISHA
Aichi-ken 471 (JP)

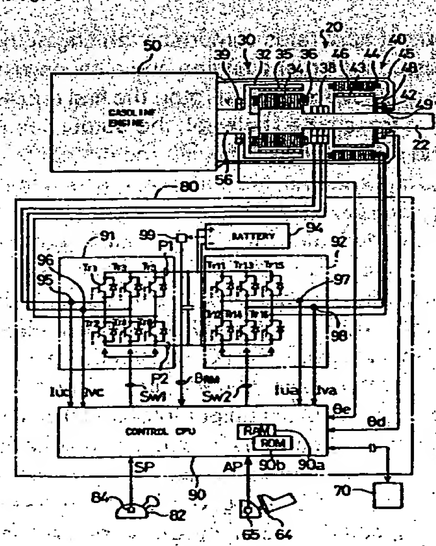
(72) Inventors:
- Yamada, Eiji,
c/o Toyota Jidosha K.K.
Toyota-shi, Aichi-ken, 471 (JP)
- Miyatani, Takao
c/o Toyota Jidosha K.K.
Toyota-shi, Aichi-ken, 471 (JP)
- Kawabata, Yasutomo,
c/o Toyota Jidosha K.K.
Toyota-shi, Aichi-ken, 471 (JP)
- Kanamori, Akihiko,
c/o Toyota Jidosha K.K.
Toyota-shi, Aichi-ken, 471 (JP)

(74) Representative: KUHNEN, WACKER & PARTNER
Alois-Steinecker-Strasse 22
D-85354 Freising (DE)

(54) Hybrid vehicle power output apparatus and method of controlling the same

(57) A power output apparatus (20) of the present invention includes a clutch motor (30), an assist motor (40), and a controller (80) for controlling the clutch motor (30) and the assist motor (40). The clutch motor (30) includes an outer rotor (32) linked with a crankshaft (56) of a gasoline engine (50) and an inner rotor (34) connecting with a drive shaft (22). The assist motor (40) includes a rotor (42) connecting with the drive shaft (22). When the residual capacity of a battery (94) is less than an allowable minimum value, a control CPU (90) of the controller (80) controls a first driving circuit (91) to enable the clutch motor (30) to carry out the power operation and apply a first torque to the drive shaft (22) in the direction of rotation of the drive shaft (22). The control CPU (90) concurrently controls a second driving circuit (92) to enable the assist motor (40) to carry out the regenerative operation and apply a second torque to the drive shaft (22) in the reverse of the rotation of the drive shaft (22). The second torque is substantially equal in magnitude but opposite in direction to the first torque. The electric power regenerated by the assist motor (40) is supplied to the battery (94) to supplement the electric power of the battery (94). The power output apparatus (20) of the invention can thus make the torque output to the drive shaft (22) approximately equal to zero.

Fig. 1



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In accordance with another aspect of the present invention, the first power output apparatus further comprises: storage means for storing electric power; and wherein the control means comprises means for controlling the first motor-driving means to supply the electric power stored in the storage means to the first motor in order to activate the first motor, and controlling the second motor-driving means to supply the electric power stored in the storage means to the second motor in order to activate the second motor.

This structure can make the output torque of the drive shaft approximately equal to zero while driving the first motor and the second motor with the electric power stored in the storage means. This structure consumes the electric power in the storage means and is thus suitable for the cases that the storage means has an excess residual capacity of electric power.

In accordance with still another aspect of the present invention, wherein the control means comprises means for controlling the second motor-driving means to enable the second motor to regenerate electric power, and controlling the first motor-driving means to supply the regenerated electric power to the first motor in order to activate the first motor.

This structure can make the output torque of the drive shaft approximately equal to zero. The electric power regenerated by the second motor is primarily consumed by the first motor, while the remaining electric power may be used for another purpose.

In accordance with still another aspect of the present invention, the first power output apparatus further comprises: storage means for storing electric power; and wherein the control means comprises means for controlling the first motor-driving means to enable the first motor to regenerate electric power, and controlling the second motor-driving means to supply the regenerated electric power and the electric power stored in the storage means to the second motor in order to activate the second motor.

This structure can make the output torque of the drive shaft approximately equal to zero. The second motor is driven with the electric power stored in the storage means as well as the regenerated electric power. This structure consumes the electric power in the storage means and is thus suitable for the cases that the storage means has an excess residual capacity of electric power.

According to another aspect of the present invention, a second power output apparatus for outputting power to a drive shaft comprises: an engine having an output shaft and applying a first torque to the output shaft; a first motor comprising a first rotor connected with the output shaft of the engine and a second rotor connected with the drive shaft, the second rotor being coaxial to and rotatable relative to the first rotor, the first and second rotors being electromagnetically coupled with each other, whereby power is transmitted between the output shaft of the engine and the drive shaft via the electromagnetic coupling of the first and second rotors; first motor-driving means for exchanging electric currents with the first motor to vary the electromagnetic coupling of the first rotor with the second rotor; a second motor comprising a stator and a third rotor connected with the drive shaft, the stator being electromagnetically coupled with the third rotor, the second motor applying a second torque to the drive shaft; second motor-driving means for exchanging electric currents with the second motor to vary the electromagnetic coupling of the stator with the third rotor; and control means for controlling the first motor-driving means to electromagnetically lock up the first rotor relative to the second rotor of the first motor and thereby allow the output shaft of the engine to rotate with the drive shaft in a substantially integral manner, and controlling the second motor-driving means to enable the second motor to regenerate lectric power, the second torque being substantially equal in magnitude in opposite direction to the first torque.

The structure of the second power output apparatus can make the output torque of the drive shaft approximately equal to zero while enabling the second motor to regenerate electric power. This structure is especially suitable for the cases requiring additional electric power.

According to still another aspect of the present invention, a third power output apparatus for outputting power to a drive shaft comprises: an engine having an output shaft; a first motor comprising a first rotor connected with the output shaft of the engine and a second rotor connected with the drive shaft, the second rotor being coaxial to and rotatable relative to the first rotor, the first and second rotors being electromagnetically coupled with each other, whereby power is transmitted between the output shaft of the engine and the drive shaft via the electromagnetic coupling of the first and second rotors; first motor-driving means for exchanging electric currents with the first motor to vary the electromagnetic coupling of the first rotor with the second rotor; a second motor comprising a stator and a third rotor connected with the drive shaft, the stator being electromagnetically coupled with the third rotor; second motor-driving means for exchanging electric currents with the second motor to vary the electromagnetic coupling of the stator with the third rotor; storage means for storing electric power; and control means for controlling the first motor-driving means to electromagnetically lock up the first rotor relative to the second rotor of the first motor and thereby allow the output shaft of the engine to rotate with the drive shaft in a substantially integral manner, and controlling the second motor-driving means to supply the electric power stored in the storage means to the second motor in order to activate the second motor and thereby make the second motor apply a torque to the drive shaft.

In th third power output apparatus of the present invention, the control means controls the first motor-driving means to electromagnetically lock up the first rotor relative to the second rotor of the first motor and thereby allow the output shaft of the engine to rotate with the drive shaft in a substantially integral manner. The control means concur-

first and second rotors being electromagnetically coupled with each other, whereby power is transmitted between the output shaft of the engine and the drive shaft via the electromagnetic coupling of the first and second rotors; a second motor comprising a stator and a third rotor connecting with either one of the drive shaft and the output shaft of the engine; driving condition detecting means for detecting a driving condition of the transportation system; and control means for, when the driving condition detected by the driving condition detecting means represents a predetermined state, controlling the engine, the first motor, and the second motor to make a torque output to the drive shaft approximately equal to zero.

This enables the current driving condition to be maintained.

According to still another aspect of the present invention, a seventh power output apparatus for outputting power to a drive shaft comprises: an engine connected with a rotating shaft; a first motor connected with the drive shaft shaft; and a second motor connected with the rotating shaft; wherein the engine produces mechanical energy and transmits the mechanical energy to the rotating shaft; the first motor converts part of the mechanical energy transmitted via the rotating shaft to electrical energy while transmits the residual mechanical energy to the second motor; and the second motor converts the mechanical energy transmitted from the first motor to electrical energy without transmitting any mechanical energy to the drive shaft.

This structure, which converts the mechanical energy output from the engine to electrical energy with the first motor and the second motor, is especially suitable for the cases requiring a large mass of electrical energy.

According to still another aspect of the present invention, a eighth power output apparatus for outputting mechanical energy as power to a drive shaft comprises: an engine connected with a rotating shaft; a first motor connected with the rotating shaft; a second motor connected with the drive shaft; and storage means for storing electrical energy; wherein the first motor converts the electrical energy supplied from the storage means to mechanical energy and transmits the sum of the mechanical energy converted from the electrical energy and mechanical energy transmitted from a second motor to the rotating shaft; the second motor converts the electrical energy supplied from the storage means to mechanical energy and transmits the mechanical energy to the first motor without transmitting any mechanical energy to the drive shaft; and the engine converts the mechanical energy transmitted via the rotating shaft to another form of energy.

The structure of the eighth power output apparatus does not transmit any mechanical energy to the drive shaft, thereby enabling the output torque of the drive shaft to be approximately equal to zero. The electrical energy stored in the storage means is converted to mechanical energy and then to heat or another form of energy. This decreases the electrical energy stored in the storage means. This structure is especially suitable for the cases that the storage means has excess electrical energy.

According to still another aspect of the present invention, a ninth power output apparatus for outputting mechanical energy as power to a drive shaft comprises: an engine connected with a rotating shaft; a first motor connected with the rotating shaft; and a second motor connected with the drive shaft; wherein the engine produces mechanical energy and transmits the mechanical energy to the rotating shaft; the first motor converts electrical energy supplied from the second motor to mechanical energy and transmits the sum of the mechanical energy converted from the electrical energy and the mechanical energy transmitted via the rotating shaft to the second motor; and the second motor converts the mechanical energy transmitted from the first motor to electrical energy without transmitting any mechanical energy to the drive shaft, and supplies part of the electrical energy converted from the mechanical energy to the first motor.

The structure of the ninth power output apparatus does not transmit any mechanical energy to the drive shaft, thereby enabling the output torque of the drive shaft to be approximately equal to zero. Part of the electrical energy obtained by the second motor is supplied to the first motor and converted to mechanical energy. The residual electrical energy may be used for another purpose according to the requirements.

According to still another aspect of the present invention, a tenth power output apparatus for outputting mechanical energy as power to a drive shaft comprises: an engine connected with a rotating shaft; a first motor connected with the rotating shaft; a second motor connected with the drive shaft; and storage means for storing electrical energy; wherein the first motor converts part of mechanical energy transmitted from the second motor to electrical energy, supplies the electrical energy to the second motor, and transmits the residual mechanical energy to the rotating shaft; the second motor converts the electrical energy supplied from the first motor and the electrical energy supplied from the storage means to mechanical energy, and transmits the mechanical energy to the first motor without transmitting any mechanical energy to the drive shaft; and the engine for converts the mechanical energy transmitted via the rotating shaft to another form of energy.

The structure of the tenth power output apparatus does not transmit any mechanical energy to the drive shaft, thereby enabling the output torque of the drive shaft to be approximately equal to zero. The electrical energy stored in the storage means is converted to mechanical energy and then to heat or another form of energy. This decreases the electrical energy stored in the storage means. This structure is especially suitable for the cases that the storage means has excess electrical energy.

The above objects are also realized by a method of controlling a power output apparatus for outputting power to a drive shaft.

Fig. 4 shows torques applied to the drive shaft 22 and the crankshaft 56 of the power output apparatus 20 of Fig. 1 in a first arrangement of operation;

Fig. 5 shows torques applied to the drive shaft 22 and the crankshaft 56 of the power output apparatus 20 of Fig. 1 in a second arrangement of operation;

Fig. 6 is a flowchart showing a control routine executed by the control CPU 90 of the power output apparatus 20 to enable the vehicle to fall in a free running state under a normal driving condition;

Fig. 7 is a flowchart showing details of an electric power-supplying process executed at step S32 in the flowchart of Fig. 6;

Fig. 8 is a flowchart showing details of a control process of the clutch motor 30 executed at step S38 in the flowchart of Fig. 6;

Fig. 9 is a flowchart showing details of a control process of the assist motor 40 executed at step S40 in the flowchart of Fig. 6;

Fig. 10 is a graph schematically illustrating an amount of energy regenerated by the clutch motor 30 and that regenerated by the assist motor 40 in the first arrangement of operation;

Fig. 11 shows a flow of energy between the gasoline engine 50, the clutch motor 30, the assist motor 40, and the battery 94 in the first arrangement of operation;

Fig. 12 is a flowchart showing details of an electric power-consuming process executed at step S36 in the flowchart of Fig. 6;

Fig. 13 is a graph schematically illustrating an amount of energy converted by the clutch motor 30 and that converted by the assist motor 40 in the second arrangement of operation;

Fig. 14 shows a flow of energy between the gasoline engine 50, the clutch motor 30, the assist motor 40, and the battery 94 in the second arrangement of operation;

Fig. 15 is a flowchart showing details of an electric power-maintaining process executed at step S34 in the flowchart of Fig. 6;

Fig. 16 is a flowchart showing a control routine executed by the control CPU 90 of the power output apparatus 20 to enable the vehicle to fall in a free running state under an overdrive condition as a second embodiment according to the present invention;

Fig. 17 is a graph schematically illustrating an amount of energy converted by the clutch motor 30 and that regenerated by the assist motor 40 in a fourth arrangement of operation;

Fig. 18 shows a flow of energy between the gasoline engine 50, the clutch motor 30, the assist motor 40, and the battery 94 in the fourth arrangement of operation;

Fig. 19 is a flowchart showing details of an electric power-consuming process executed at step S76 in the flowchart of Fig. 16;

Fig. 20 is a graph schematically illustrating an amount of energy regenerated by the clutch motor 30 and that converted by the assist motor 40 in a fifth arrangement of operation;

Fig. 21 shows a flow of energy between the gasoline engine 50, the clutch motor 30, the assist motor 40, and the battery 94 in the fifth arrangement of operation;

Fig. 22 shows torques applied to the drive shaft 22 and the crankshaft 56 of the power output apparatus 20 in a sixth arrangement of operation as a third embodiment according to the present invention;

As shown in Fig. 1, the clutch motor 30 is constructed as a synchronous motor having permanent magnets 35 attached to an inner surface of the outer rotor 32 and three-phase coils 36 wound on slots formed in the inner rotor 34. Power is supplied to the three-phase coils 36 via a rotary transformer 38. A thin laminated sheet of non-directional electromagnetic steel is used to form teeth and slots for the three-phase coils 36 in the inner rotor 34. A resolver 39 for measuring a rotational angle θe of the crankshaft 56 is attached to the crankshaft 56. The resolver 39 may also serve as the angle sensor 78 mounted on the distributor 60.

The assist motor 40 is also constructed as a synchronous motor having three-phase coils 44, which are wound on a stator 43 fixed to a casing 45 to generate a rotating magnetic field. The stator 43 is also made of a thin laminated sheet of non-directional electromagnetic steel. A plurality of permanent magnets 46 are attached to an outer surface of the rotor 42. In the assist motor 40, interaction between a magnetic field formed by the permanent magnets 46 and a rotating magnetic field formed by the three-phase coils 44 leads to rotation of the rotor 42. The rotor 42 is mechanically linked with the drive shaft 22 working as the torque output shaft of the power output apparatus 20. A resolver 48 for measuring a rotational angle θd of the drive shaft 22 is attached to the drive shaft 22, which is further supported by a bearing 49 held in the casing 45.

The inner rotor 34 of the clutch motor 30 is mechanically linked with the rotor 42 of the assist motor 40 and further with the drive shaft 22. When the rotation and axial torque of the crankshaft 56 of the gasoline engine 50 are transmitted via the outer rotor 32 to the inner rotor 34 of the clutch motor 30, the rotation and torque by the assist motor 40 are added to or subtracted from the transmitted rotation and torque.

While the assist motor 40 is constructed as a conventional permanent magnet-type three-phase synchronous motor, the clutch motor 30 includes two rotating elements or rotors, that is, the outer rotor 32 with the permanent magnets 35 and the inner rotor 34 with the three-phase coils 36. The detailed structure of the clutch motor 30 is described with the cross sectional view of Fig. 2. The outer rotor 32 of the clutch motor 30 is attached to a circumferential end of a wheel 57 set around the crankshaft 56, by means of a pressure pin 59a and a screw 59b. A central portion of the wheel 57 is protruded to form a shaft-like element, to which the inner rotor 34 is rotatably attached by means of bearings 37A and 37B. One end of the drive shaft 22 is fixed to the inner rotor 34.

A plurality of permanent magnets 35, four in this embodiment, are attached to the inner surface of the outer rotor 32 as mentioned previously. The permanent magnets 35 are magnetized in the direction towards the axial center of the clutch motor 30, and have magnetic poles of alternately inverted directions. The three-phase coils 36 of the inner rotor 34 facing to the permanent magnets 35 across a little gap are wound on a total of 24 slots (not shown) formed in the inner rotor 34. Supply of electricity to the respective coils forms magnetic fluxes running through the teeth (not shown), which separate the slots from one another. Supply of a three-phase alternating current to the respective coils rotates this magnetic field. The three-phase coils 36 are connected to receive electric power supplied from the rotary transformer 38. The rotary transformer 38 includes primary windings 38a fixed to the casing 45 and secondary windings 38b attached to the drive shaft 22 coupled with the inner rotor 34. Electromagnetic induction allows electric power to be transmitted from the primary windings 38a to the secondary windings 38b or vice versa. The rotary transformer 38 has windings for three phases, that is, U, V, and W phases, to enable the transmission of three-phase electric currents.

Interaction between a magnetic field formed by one adjacent pair of permanent magnets 35 and a rotating magnetic field formed by the three-phase coils 36 of the inner rotor 34 leads to a variety of behaviors of the outer rotor 32 and the inner rotor 34. The frequency of the three-phase alternating current supplied to the three-phase coils 36 is generally equal to a difference between the revolving speed (revolutions per second) of the outer rotor 32 directly connected to the crankshaft 56 and the revolving speed of the inner rotor 34. This results in a slip between the rotations of the outer rotor 32 and the inner rotor 34. Details of the control procedures of the clutch motor 30 and the assist motor 40 will be described later based on the flowcharts.

As mentioned above, the clutch motor 30 and the assist motor 40 are driven and controlled by the controller 80. Referring back to Fig. 1, the controller 80 includes a first driving circuit 91 for driving the clutch motor 30, a second driving circuit 92 for driving the assist motor 40, a control CPU 90 for controlling both the first and second driving circuits 91 and 92, and a battery 94 including a number of secondary cells. The control CPU 90 is a one-chip microprocessor including a RAM 90a used as a working memory, a ROM 90b in which various control programs are stored, an input/output port (not shown), and a serial communication port (not shown) through which data are sent to and received from the EFIECU 70. The control CPU 90 receives a variety of data through the input/output port. The input data include a rotational angle θe of the crankshaft 56 of the gasoline engine 50 from the resolver 39, a rotational angle θd of the drive shaft 22 from the resolver 48, an accelerator pedal position AP (step-on amount of the accelerator pedal 64) from the accelerator position sensor 65, a gearshift position SP from the gearshift position sensor 84, clutch motor currents Iuc and Ivc from two ammeters 95 and 96 in the first driving circuit 91, assist motor currents Iua and Iva from two any known method; for example, by measuring the specific gravity of an electrolytic solution in the battery 94 or the whole weight of the battery 94, by computing the currents and time of charge and discharge, or by causing an instantaneous short-circuit between terminals of the battery 94 and measuring an internal resistance against the electric current.

The control CPU 90 outputs a first control signal SW1 for driving six transistors Tr1 through Tr6 working as switching elements of the first driving circuit 91 and a second control signal SW2 for driving six transistors Tr11 through Tr16 work-

Fig. 5 shows torques applied to the drive shaft 22 and the crankshaft 56 of the power output apparatus 20 of Fig. 1 in the second arrangement of operation. As mentioned previously, both the clutch motor 30 and the assist motor 40 are controlled to implement the power operation in the second arrangement of operation. The crankshaft 56 receives a torque Tc produced by the clutch motor 30 in the direction of rotation of the crankshaft 56. Since the torque Tc acts to enhance the rotation of the crankshaft 56, the gasoline engine 50 exerts an effect of engine brake. The crankshaft 56 accordingly receives a friction torque Tef produced by the gasoline engine 50, which is equal in magnitude but opposite in direction to the torque Tc. The drive shaft 22, on the other hand, receives a torque Tc produced by the clutch motor 30 in the reverse of the rotation of the drive shaft 22 as well as a torque Ta produced by the assist motor 40 in the direction of rotation of the drive shaft 22. The torque Tc applied to the drive shaft 22 by the clutch motor 30 is opposite in direction to the torque Ta applied to the drive shaft 22 by the assist motor 40. Provided that the magnitude of the torque Tc is identical with that of the torque Ta, the torques Tc and Ta cancel each other on the drive shaft 22. The output torque Td of the drive shaft 22 thus becomes substantially equal to zero. Like the first arrangement of operation shown in Fig. 4, the torque Tc of the clutch motor 30 applied to the drive shaft 22 is a reaction of the torque Tc applied to the crankshaft 56 in the second arrangement of operation shown in Fig. 5.

When the residual capacity BRM of the battery 94 is determined to be within the allowable range, the control CPU 90 controls the first driving circuit 91 and the second driving circuit 92 to prevent electric currents from flowing through the three-phase coils 36 of the clutch motor 30 and the three-phase coils 44 of the assist motor 40, respectively. This corresponds to a third arrangement of operation, in which the control CPU 90 disconnects the electromagnetic coupling of the outer rotor 32 with the inner rotor 34 in the clutch motor 30 as well as the electromagnetic coupling of the rotor 42 with the stator 43 in the assist motor 40. Under such conditions, no torques are applied to the drive shaft 22 by either the clutch motor 30 or the assist motor 40. The output torque Td of the drive shaft 22 thus becomes substantially equal to zero.

It is, however, not required to completely cut off the electromagnetic coupling of the outer rotor 32 with the inner rotor 34 or the same of the rotor 42 with the stator 43, as long as practical disconnection is attained. In this state, weak electric currents may flow through the three-phase coils 36 of the clutch motor 30 and the three-phase coils 44 of the assist motor 40 to maintain the weak coupling, as long as substantially no torques are applied to the drive shaft 22 by either the clutch motor 30 or the assist motor 40.

The vehicle falls in a free running state when the output torque of the drive shaft 22 is made substantially equal to zero as discussed above.

The following gives detailed description of the control procedure executed by the controller 80 to enable free running of the vehicle when the vehicle is in a normal driving state (that is, when the revolving speed of the drive shaft 22 is lower than that of the crankshaft 56 of the gasoline engine 50). Fig. 6 is a flowchart showing a control routine executed by the control CPU 90 of the controller 80 to enable the vehicle to fall in a free running state under the normal driving condition. When the program enters the routine, the control CPU 90 first receives data of revolving speed Nd of the drive shaft 22 at step S20. The revolving speed Nd of the drive shaft 22 can be computed from the rotational angle θd of the drive shaft 22 read from the resolver 48.

At subsequent step S22, the control CPU 90 reads the accelerator pedal position AP output from the accelerator position sensor 65. The driver steps on the accelerator pedal 64 when feeling insufficiency of output torque. The value of the accelerator pedal position AP accordingly represents the desired output torque (that is, desired torque of the drive shaft 22) which the driver requires. It is then determined at step S24 whether the input accelerator pedal position AP is equal to zero. The accelerator pedal position AP=0 (that is, the step-on amount of the accelerator pedal 64 equal to zero) represents the case in which the driver does not step on the accelerator pedal 64 but desires the vehicle to maintain the current driving condition. In other words, the driver does not need the output torque of the drive shaft 22 but requires free running of the vehicle. When the accelerator pedal position AP is equal to zero, the program proceeds to step S26 for the free running control. When the accelerator pedal position AP is not equal to zero, on the other hand, the program determines that the driver does not require any free running of the vehicle and directly exits from this routine.

At step S26, the control CPU 90 reads the residual capacity BRM of the battery 94 from the residual capacity meter 99. The input residual capacity BRM is compared with an allowable minimum value Bmin at step S28 and subsequently with an allowable maximum value Bmax at step S30. The residual capacity BRM of the battery 94 has an allowable range. The life of the battery 94 may undesirably be shortened when the residual capacity BRM is kept out of the allowable range. In this embodiment, the allowable minimum value Bmin and the allowable maximum value Bmax are previously set as the minimum value and the maximum value of the allowable range. When the residual capacity BRM is less than the allowable minimum value Bmin, the first arrangement of operation is selected to enable both the clutch motor 30 and the assist motor 40 to carry out the regenerative operation and supply the regenerated electric power to the battery 94. When the residual capacity BRM is greater than the allowable maximum value Bmax, on the contrary, the second arrangement of operation is selected to enable both the clutch motor 30 and the assist motor 40 to carry out th power operation and consume the electric power stored in the battery 94. The residual capacity BRM of the battery 94

assist motor 40 by interrupt processing, while transmitting an instruction to the EFIECU 70 through communication to enable the EFIECU 70 to control the gasoline engine 50 concurrently.

Fig. 8 is a flowchart showing details of the control process of the clutch motor 30 executed at step S38 in the flowchart of Fig. 6. When the program enters the clutch motor control routine, the control CPU 90 of the controller 80 first reads the rotational angle θd of the drive shaft 22 from the resolver 48 at step S112 and the rotational angle θe of the crankshaft 56 of the gasoline engine 50 from the resolver 39 at step S114. The control CPU 90 then computes a relative angle θc of the drive shaft 22 and the crankshaft 56 by the equation $\theta c = \theta e - \theta d$ at step S116.

The program proceeds to step S118, at which the control CPU 90 receives data of clutch motor currents Iuc and Ivc, which respectively flow through the U phase and V phase of the three-phase coils 36 in the clutch motor 30, from the ammeters 95 and 96. Although the currents naturally flow through all the three phases U, V, and W, measurement is required only for the currents passing through the two phases since the sum of the currents is equal to zero. At subsequent step S120, the control CPU 90 executes transformation of coordinates (three-phase to two-phase transformation) using the values of currents flowing through the three phases obtained at step S118. The transformation of coordinates maps the values of currents flowing through the three phases to the values of currents passing through d and q axes of the permanent magnet-type synchronous motor and is executed according to Equation (1) given below:

$$\begin{bmatrix} Idc \\ Iqc \end{bmatrix} = \sqrt{2} \begin{bmatrix} -\sin(\theta c - 120) & \sin \theta c \\ -\cos(\theta c - 120) & \cos \theta c \end{bmatrix} \begin{bmatrix} Iuc \\ Ivc \end{bmatrix} \tag{1}$$

The transformation of coordinates is carried out because the currents flowing through the d and q axes are essential for the torque control in the permanent magnet-type synchronous motor. Alternatively, the torque control may be executed directly with the currents flowing through the three phases. After the transformation to the currents of two axes, the control CPU 90 computes deviations of currents Idc and Iqc actually flowing through the d and q axes from current command values Idc* and Iqc* of the respective axes, which are calculated from the torque command value Tc* of the clutch motor 30, and determines voltage command values Vdc and Vqc for the d and q axes at step S122. In accordance with a concrete procedure, the control CPU 90 executes operations following Equations (2) and Equations (3) given below:

$$\Delta Idc = Idc^* - Idc \quad \Delta Iqc = Iqc^* - Iqc \tag{2}$$

$$Vdc = Kp1 \cdot \Delta Idc + \Sigma Ki1 \cdot \Delta Idc \quad Vqc = Kp2 \cdot \Delta Iqc + \Sigma Ki2 \cdot \Delta Iqc \tag{3}$$

wherein Kp1, Kp2, Ki1, and Ki2 represent coefficients, which are adjusted to be suited to the characteristics of the motor applied.

The voltage command value Vdc (Vqc) includes a part in proportion to the deviation ΔI from the current command value I* (first term in right side of Equation (3)) and a summation of historical data of the deviations ΔI for 'i' times (second term in right side). The control CPU 90 then re-transforms the coordinates of the voltage command values thus obtained (two-phase to three-phase transformation) at step S124. This corresponds to an inverse of the transformation executed at step S120. The inverse transformation determines voltages Vuc, Vvc, and Vwc actually applied to the three-phase coils 36 as given below:

$$\begin{bmatrix} Vuc \\ Vvc \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos \theta c & -\sin \theta c \\ \cos(\theta c - 120) & -\sin(\theta c - 120) \end{bmatrix} \begin{bmatrix} Vdc \\ Vqc \end{bmatrix} \tag{4}$$
$$Vwc = -Vuc - Vvc$$

The actual voltage control is accomplished by on-off operation of the transistors Tr1 through Tr6 in the first driving circuit 91. At step S126, the on- and off-time of the transistors Tr1 through Tr6 in the first driving circuit 91 is PWM (pulse width modulation) controlled in order to attain the voltage command values Vuc, Vvc, and Vwc determined by Equation (4) above. This process enables the clutch motor 30 to mechanically transmit the target torque to the drive shaft 22.

Fig. 9 is a flowchart showing details of the control process of the assist motor 40 executed at step S40 in the flowchart of Fig. 6. When the program enters the assist motor control routine, the control CPU 90 first reads the rotational angle θd of the drive shaft 22 from the resolver 48 at step S140, and receives data of assist motor currents Iua and Iva, which respectively flow through the U phase and V phase of the three-phase coils 44 in the assist motor 40, from the ammeters 97 and 98 at step S142. The control CPU 90 then executes transformation of coordinates for the currents of the three phases at step S144, computes voltage command values Vda and Vqa at step S146, and executes inverse transformation of coordinates for the voltage command values at step S148. At subsequent step S150, the control CPU 90 determines the on- and off-time of the transistors Tr11 through Tr16 in the second driving circuit 92 for PWM (pulse width modulation) control. The processing executed at steps S144 through S150 is similar to that executed at steps S120 through S126 of the clutch motor control routine shown in the flowchart of Fig. 8.

In the second arrangement of operation shown in Fig. 5 when both the clutch motor 30 and the assist motor 40 are controlled to carry out the power operation, in order to set the output torque Td of the drive shaft 22 practically equal to zero, it is required to make the torque Tc of the clutch motor 30 and the torque Ta of the assist motor 40 substantially equal in magnitude to each other and cancel each other on the drive shaft 22. The first requirement is thus to set the torque command value Tc* of the clutch motor 30 equal in magnitude to the torque command value Ta* of the assist motor 40 as given below:

$$|Tc^*| = |Ta^*|$$

It is also required to make the total of electric power consumed by the clutch motor 30 and the assist motor 40 less than the consumable electric power Wu which can be taken out of the battery 94. The second requirement is thus to set the torque command value Tc* of the clutch motor 30 and the torque command value Ta* of the assist motor 40 which can fulfill the relationship that the sum of electric power Pc consumed by the clutch motor 30 and electric power Pa consumed by the assist motor 40 is less than the consumable electric power Wu as given below:

$$Wu \geq Pa + Pc$$

The electric power Pc consumed by the clutch motor 30 is expressed as:

$$Pc = (1/ksc) \times |Tc^*| \times (Nd\text{-}Ne)$$

wherein ksc represents the efficiency of power operation of the clutch motor 30. The electric power Pa consumed by the assist motor 40 is expressed as:

$$Pa = (1/ksa) \times |Ta^*| \times Nd$$

wherein ksa represents the efficiency of power operation of the assist motor 40.

After concluding the processing of step S54, the program exits from the routine of electric power-consuming process of Fig. 12 and returns to the control routine shown in the flowchart of Fig. 6. The control CPU 90 carries out the control procedures to control the clutch motor 30 at step S38, the assist motor 40 at step S40, and the gasoline engine 50 at step S42. The control processes of the clutch motor 30 and the assist motor 40 in the second arrangement of operation are similar to those of Figs 8 and 9 executed in the first arrangement of operation. Unlike the first arrangement of operation, however, both the clutch motor 30 and the assist motor 40 are controlled to implement not the regenerative operation but the power operation in the second arrangement of operation. The torques produced by the clutch motor 30 and the assist motor 40 in the second arrangement of operation are accordingly opposite in direction to those in the first arrangement of operation. Note that the torque command value Tc* of the clutch motor 30 and the torque command value Ta* of the assist motor 40 in the second arrangement thereby have reverse signs to those in the first arrangement.

The control of the gasoline engine 50 does not follow the method carried out in the first arrangement of operation. In the second arrangement of operation, the gasoline engine 50 is controlled to come into an idling state in order to attain an effect of engine brake. In accordance with a concrete procedure, the control CPU 90 sends an instruction to the EFIECU 70 through communication to enable the EFIECU 70 to decrease the amount of fuel injection or the throttle valv position. Such regulation makes the gasoline engine 50 fall in an idling state. As shown in Fig. 5, the friction torque having the same magnitude as that of the torque Tc of the clutch motor 30 is applied to the crankshaft 56 in the reverse of the rotation of the crankshaft 56. The friction torque includes the torque produced by the actual friction as well as the torque produced as resistivity in the gasoline engine 50 when the air in the cylinder is compressed by the piston or when the air is ingested into the cylinder. When the gasoline engine 50 has a function of exhaust braking, a greater torque may be produced by activating the exhaust brake.

In accordance with another preferred structure, the fuel injection may be stopped to cease the operation of the gasoline engine 50. This structure also enables the friction torque by the gasoline engine 50 to be applied to the crankshaft 56.

In the second arrangement of operation, both the clutch motor 30 and the assist motor 40 are controlled to implement the power operation with the electric power supplied from the battery 94 and thereby consume the electric power stored in the battery 94. The power operation of the clutch motor 30 and the assist motor 40 causes the torque Tc of the clutch motor 30 to act on the drive shaft 22 opposite in direction to the torque Ta of the assist motor 40. Since the torque Tc and the torque Ta are equal to each other in magnitude, the torque Tc and the torque Ta cancel each other on the drive shaft 22. This makes the output torque Td of the drive shaft 22 substantially equal to zero, thereby realizing a free running state of the vehicle.

Fig. 13 is a graph schematically illustrating an amount of energy converted by the clutch motor 30 and that converted by the assist motor 40 in the second arrangement of operation. The clutch motor 30 produces the torque Tc while

of the battery 94 is greater than the allowable maximum value Bmax, on the contrary, the structure of the first embodiment enables the vehicle to fall in the free running state while consuming the electric power of the battery 94.

The power output apparatus 20 of the first embodiment can go into another application given as a second embodiment of the present invention. In the first embodiment, the vehicle is set into a free running state while being driven under the normal driving condition (that is, when the drive shaft 22 is rotated at a lower revolving speed than that of the crankshaft 56 of the gasoline engine 50). It is also possible to make the vehicle come into the free running state while being driven under the high-speed driving condition or overdrive condition. In the overdrive state, the drive shaft 22 is rotated at a revolving speed higher than that of the crankshaft 56 of the gasoline engine 50. In the second embodiment, the vehicle is set into the free running state while being driven under the high-speed driving condition or overdrive condition.

The following describes the operation when the vehicle is driven in the overdrive state and runs, for example, an expressway at a high speed. By way of example, it is assumed that the gasoline engine 50 driven by the EFIECU 70 rotates at a predetermined revolving speed Ne and that the drive shaft 22 rotates in the direction of rotation of the crankshaft 56 at a revolving speed Nd higher than the predetermined revolving speed Ne (Nd>Ne).

In the same manner as the first embodiment, the control CPU 90 of the controller 80 refers to the output data of the residual capacity meter 99 and determines whether the residual capacity BRM of the battery 94 is out of the allowable range or within the allowable range. The control CPU 90 controls the first and the second driving circuits 91 and 92 based on the results of determination.

When the residual capacity BRM of the battery 94 is smaller than the allowable minimum value Bmin and thus determined to be out of the allowable range, the power output apparatus 20 is set into a fourth arrangement of operation. In the fourth arrangement of operation, the assist motor 40 is controlled to carry out the regenerative operation and regenerate electric power via the second driving circuit 92. The clutch motor 30 is controlled via the first driving circuit 91 to implement the power operation with part of the regenerated electric power. The residual electric power is supplied to the battery 94 to supplement the electric power of the battery 94.

Torques applied to the drive shaft 22 and the crankshaft 56 of the power output apparatus 20 in the fourth arrangement of operation are identical with those illustrated in Fig. 4. By way of example, it is assumed that the crankshaft 56 of the gasoline engine 50 is rotated at a predetermined revolving speed Ne in the direction defined by the open arrow of Fig. 4, while the drive shaft 22 is rotated in the same direction defined by the open arrow at a revolving speed Nd, which is higher than the revolving speed Ne (Nd>Ne). When the clutch motor 30 is controlled to carry out the power operation, the crankshaft 56 receives a torque Tc produced by the clutch motor 30 in the reverse of the rotation of the crankshaft 56. The drive shaft 22, on the other hand, receives a torque Tc produced by the clutch motor 30 in the direction of rotation of the drive shaft 22. The torque Tc of the clutch motor 30 applied to the drive shaft 22 is a reaction of the torque Tc applied to the crankshaft 56. The torques Tc produced by the clutch motor 30 when the clutch motor 30 carries out the regenerative operation in the normal driving state (when the drive shaft 22 is rotated at the revolving speed Nd lower than the revolving speed Ne of the crankshaft 56) are equal in direction to those produced by the clutch motor 30 when the clutch motor 30 carries out the power operation in the high-speed driving state or overdrive state (when the drive shaft 22 is rotated at the revolving speed Nd higher than the revolving speed Ne of the crankshaft 56). The crankshaft 56 also receives a torque Te produced by the gasoline engine 50 in the direction of rotation of the crankshaft 56. In a stationary state where the revolving speed Ne of the crankshaft 56 is practically kept constant, the torque Te substantially balances with the torque Tc. This means that the magnitude of the torque Te is substantially equal to that of the torque Tc. When the assist motor 40 is controlled to carry out the regenerative operation, the drive shaft 22 receives a torque Ta produced by the assist motor 40 in the reverse of the rotation of the drive shaft 22. The torque Tc applied to the drive shaft 22 by the clutch motor 30 is opposite in direction to the torque Ta applied to the drive shaft 22 by the assist motor 40. Provided that the magnitude of the torque Tc is identical with that of the torque Ta, the torques Tc and Ta cancel each other on the drive shaft 22. The output torque Td of the drive shaft 22 thus becomes substantially equal to zero.

When the residual capacity BRM of the battery 94 is greater than the allowable maximum value Bmax and thus determined to be out of the allowable range, on the other hand, the power output apparatus 20 is set into a fifth arrangement of operation. In the fifth arrangement of operation, the clutch motor 30 is controlled to carry out the regenerative operation and regenerate electric power via the first driving circuit 91. The assist motor 40 carries out the power operation with the electric power regenerated by the clutch motor 30 and the electric power stored in the battery 94.

Torques applied to the drive shaft 22 and the crankshaft 56 of the power output apparatus 20 in the fifth arrangement of operation are identical with those illustrated in Fig. 5. By way of example, it is assumed that the crankshaft 56 of the gasoline engine 50 is rotated at a predetermined revolving speed Ne, while the drive shaft 22 is rotated in the same direction at a revolving speed Nd, which is higher than the revolving speed Ne (Nd>Ne). When the clutch motor 30 is controlled to carry out the regenerative operation, the crankshaft 56 receives a torque Tc produced by the clutch motor 30 in the direction of rotation of the crankshaft 56. The drive shaft 22, on the other hand, receives a torque Tc produced by the clutch motor 30 in the reverse of the rotation of the drive shaft 22. The torque Tc of the clutch motor 30 applied to the drive shaft 22 is a reaction of the torque Tc applied to the crankshaft 56. The torques Tc produced by

Ta of the assist motor 40. Since the torque Tc and the torque Ta are equal in magnitude to each other, the torque Tc and the torque Ta cancel each other on the drive shaft 22. The output torque Td of the drive shaft 22 thus becomes substantially equal to zero, thereby realizing a free running state of the vehicle. The residual electric power regenerated by the assist motor 40 is supplied to the battery 94 to supplement the electric power of the battery 94.

Fig. 17 is a graph schematically illustrating an amount of energy converted by the clutch motor 30 and that regenerated by the assist motor 40 in the fourth arrangement of operation. When the crankshaft 56 of the gasoline engine 50 is rotated at a revolving speed Ne and a torque Te, the energy output from the gasoline engine 50 is expressed as the product of the revolving speed Ne and the torque Te. The output energy (Ne×Te) of the gasoline engine 50 corresponds to the energy of a region Ge as clearly shown in Fig. 17. The revolving speed Nc of the clutch motor 30 is expressed as the difference (Nd-Ne) between the revolving speed Nd of the drive shaft 22 and the revolving speed Ne of the crankshaft 56. The torque Tc of the clutch motor 30 is equal in magnitude to the torque Te of the gasoline engine 50. Energy converted from the electric power by the clutch motor 30 corresponds to the energy of a region Gc. The revolving speed of the assist motor 40 is given as the revolving speed Nd of the drive shaft 22, while the torque Ta of the assist motor 40 is equal in magnitude to the torque Tc of the clutch motor 30. The energy regenerated as electric power by the assist motor 40 thus corresponds to the energy of a region Ga, which is the sum of the energy of the region Ge produced by the gasoline engine 50 and the energy of the region Gc produced by the clutch motor 30. Among the energy of the region Ga thus regenerated as electric power, the energy of the region Gc is supplied back to the clutch motor 30, wh reas the energy of the residual region Ge is supplied to and stored into the battery 94. In the fourth arrangement of operation, the energy of the region Ge output from the gasoline engine 50 is directly stored into the battery 94.

There are naturally certain amounts of energy loss in the clutch motor 30, the assist motor 40, the first driving circuit 91, and the second driving circuit 92. In the practical state, it is rather difficult to store all the output energy of the gasoline engine 50 corresponding to the region Ge into the battery 94. The energy loss in the clutch motor 30 and the assist motor 40 is relatively small since some synchronous motors recently developed have the efficiency very close to 1.

Fig. 18 shows a flow of energy between the gasoline engine 50, the clutch motor 30, the assist motor 40, and the battery 94 in the fourth arrangement of operation. Mechanical energy (Te×Ne) of the region Ge produced by the gasoline engine 50 is transmitted to the clutch motor 30. The clutch motor 30 converts electrical energy (Ta×Nc) supplied from the assist motor 40 to mechanical energy (Tc×Nc) of the region Gc, and transmits the sum of the converted mechanical energy (Tc×Nc) of the region Gc and the mechanical energy (Te×Ne) of the region Ge transmitted from the gasoline engine 50 to the assist motor 40. The assist motor 40 does not transmit any mechanical energy, which has been transmitted from the clutch motor 30, to the drive shaft 22, but converts all the transmitted mechanical energy to electrical energy (Ta×Nd) corresponding to the region Ga. Part of the electrical energy (Ta×Nc) is supplied to the clutch motor 30, while the residual electrical energy (Ta×Ne) is supplied to the battery 94. The battery 94 is then charged with the supplied electrical energy (Ta×Ne).

Fig. 19 is a flowchart showing details of the electric power-consuming process executed at step S76 in the flowchart of Fig. 16. The processing of steps S84 and S86 in the flowchart of Fig. 19 are identical with that of steps S50 and S52 in the flowchart of Fig. 12. The control CPU 90 subsequently sets the torque command value Tc* of the clutch motor 30 and the torque command value Ta* of the assist motor 40 at step S88. The torque command values Tc* and Ta* are determined to satisfy the following two requirements.

In the fifth arrangement of operation described with the drawing of Fig. 5 when the clutch motor 30 implements the regenerative operation while the assist motor 40 carrying out the power operation, in order to set the output torque Td of the drive shaft 22 practically equal to zero, it is required to make the torque Tc of the clutch motor 30 and the torque Ta of the assist motor 40 substantially equal in magnitude to each other and cancel each other on the drive shaft 22. The first requirement is thus to set the torque command value Tc* of the clutch motor 30 equal in magnitude to the torque command value Ta* of the assist motor 40 as given below:

$$|Tc^*| = |Ta^*|$$

The electric power stored in the battery 94 compensates for a specific part of electric power, which is consumed by the assist motor 40 but not covered by the electric power regenerated by the clutch motor 30. The specific part of electric power should be less than the consumable electric power Wu which can be taken out of the battery 94. The second requirement is thus to set the torque command value Tc* of the clutch motor 30 and the torque command value Ta* of the assist motor 40 which can fulfill the relationship that the residual electric power obtained by subtracting electric power Pc regenerated by the clutch motor 30 from electric power Pa consumed by the assist motor 40 is less than the consumable lectric power Wu as given below:

$$Wu > Pa - Pc$$

The electric power Pc regenerated by the clutch motor 30 is expressed as:

In the structure of the second embodiment, when the vehicle runs under the high-speed driving condition or overdrive condition (that is, when the drive shaft 22 is rotated at a revolving speed higher than that of the crankshaft 56 of the gasoline engine 50), the above control processes make the torque output to the drive shaft 22 substantially equal to zero, thereby realizing a free running state of the vehicle. Under the high-speed driving condition, when the residual capacity BRM of the battery 94 is less than the allowable minimum value Bmin, the structure of the second embodiment enables the vehicle to fall in the free running state while supplementing the electric power of the battery 94. When the residual capacity BRM of the battery 94 is greater than the allowable maximum value Bmax, on the contrary, the structure of the second embodiment enables the vehicle to fall in the free running state while consuming the electric power of the battery 94.

The power output apparatus 20 of the first embodiment can go into still another application given as a third embodiment of the present invention. In the first and the second embodiments, the vehicle is set into a free running state while being driven under the normal driving condition (that is, when the drive shaft 22 is rotated at a lower revolving speed than that of the crankshaft 56 of the gasoline engine 50) or while being driven under the overdrive condition (that is, when the drive shaft 22 is rotated at a higher revolving speed than that of the crankshaft 56 of the gasoline engine 50). As a special case, it is also possible to make the vehicle come into the free running state when the revolving speed of the drive shaft 22 is identical with that of the crankshaft 56 of the gasoline engine 50.

The following describes the operation in this special case. By way of example, it is assumed that the gasoline engine 50 driven by the EFIECU 70 rotates at a predetermined revolving speed Ne and that the drive shaft 22 rotates in the direction of rotation of the crankshaft 56 at a revolving speed Nd approximately equal to the predetermined revolving speed Ne ($Nd \approx Ne$).

In the same manner as the first and the second embodiments, the control CPU 90 of the controller 80 refers to the output data of the residual capacity meter 99, and determines whether the residual capacity BRM of the battery 94 is less than the allowable minimum value Bmin or greater than the allowable maximum value Bmax to be out of the allowable range or alternatively not less than the allowable minimum value Bmin and not greater than the allowable maximum value Bmax to be within the allowable range.

When the residual capacity BRM of the battery 94 is smaller than the allowable minimum value Bmin and thus determined to be out of the allowable range, the power output apparatus 20 is set into a sixth arrangement of operation. In the sixth arrangement of operation, the control CPU 90 of the controller 80 controls the first driving circuit 91 to fix the crankshaft 56 integrally with the drive shaft 22 through the electromagnetic coupling of the outer rotor 32 with the inner rotor 34 in the clutch motor 30. The state of fixing the crankshaft 56 and the drive shaft 22 integrally with each other is hereinafter referred to as the lock-up state. This is realized by enabling the three-phase coils 36 of the clutch motor 30 to generate not a revolving magnetic field but a stationary magnetic field. This makes the drive shaft 22 rotate integrally with the crankshaft 56 at an identical revolving speed. The control CPU 90 then controls the second driving circuit 92 to enable the assist motor 40 to carry out the regenerative operation and regenerate electric power via the second driving circuit 92. The electric power regenerated by the assist motor 40 is supplied to the battery 94 to supplement the electric power of the battery 94. Part of the regenerated electric power is used to maintain the lock-up state of the clutch motor 30.

Fig. 22 shows torques applied to the drive shaft 22 and the crankshaft 56 of the power output apparatus 20 in the sixth arrangement of operation. By way of example, it is assumed that the crankshaft 56 and the drive shaft 22 are rotated at an identical revolving speed ($Ne=Nd$) in the direction defined by the open arrow of Fig. 22. The crankshaft 56 receives a torque Te produced by the gasoline engine 50 in the direction of rotation of the crankshaft 56. When the assist motor 40 is controlled to carry out the regenerative operation, the drive shaft 22 receives a torque Ta produced by th assist motor 40 in the reverse of the rotation of the drive shaft 22. When the clutch motor 30 is kept in the lock-up state, the crankshaft 56 and the drive shaft 22 are fixed integrally with each other. On the stationary axis consisting of the crankshaft 56 and the drive shaft 22, the torque Te produced by the gasoline engine 50 is opposite in direction to the torque Ta produced by the assist motor 40. Provided that the magnitude of the torque Te is identical with that of the torque Ta, the torques Te and Ta cancel each other on the drive shaft 22. The output torque Td of the drive shaft 22 thus becomes substantially equal to zero, so that the vehicle is set into the free running state.

When the residual capacity BRM of the battery 94 is greater than the allowable maximum value Bmax and thus determined to be out of the allowable range, on the other hand, the power output apparatus 20 is set into a seventh arrangement of operation. In the seventh arrangement of operation, the control CPU 90 of the controller 80 controls the first driving circuit 91 to lock up the clutch motor 30. The electric power required for maintaining the lock-up state of the clutch motor 30 is supplied from the battery 94. The control CPU 90 then controls the second driving circuit 92 to enable the assist motor 40 to carry out the power operation with the electric power stored in the battery 94. Like the second and the fifth arrangements of operation described above, the control CPU 90 sends an instruction to the EFIECU 70, which then controls the gasoline engine 50 to be set in an idling state in order to attain an effect of engine brake in the seventh arrangement of op ration. In accordance with another preferred structure, the fuel injection may be stopped to cease the operation of the gasoline engine 50.

In the power output apparatus 20A of Fig. 25, the clutch motor 30A and the assist motor 40A are integrally joined with each other, which shortens the length of the power output apparatus 20A along the drive shaft 22. The outer rotor 32A functions concurrently as one of the rotors in the clutch motor 30A and as the rotor of the assist motor 40A, thereby effectively reducing the size and weight of the whole power output apparatus 20A.

The modified structure that the outer rotor 32A works as one of the rotors in the clutch motor 30A and as the rotor of the assist motor 40A causes the clutch motor 30A and the assist motor 40A to magnetically interfere with each other and thereby have adverse effects on each other. In order to prevent the large magnetic interference, the outer rotor 32A may be constructed as a double-cylinder structure including two concentric cylinders. One of the cylinders is assigned to the rotor of the clutch motor 30A, and the other to the rotor of the assist motor 40A. The two cylinders apart from each other by a predetermined distance are connected to the drive shaft 22. A magnetic shielding member for blocking the magnetic lines of force is also effective for preventing the magnetic interference.

Although the assist motor 40 is attached to the drive shaft 22 in the power output apparatus 20 of Fig. 1, an assist motor 40B may be attached to the crankshaft 56 of the gasoline engine 50 like another power output apparatus 20B shown in Fig. 26.

The power output apparatus 20B of Fig. 26 has a similar structure to that of the power output apparatus 20 of Fig. 1, except that the assist motor 40B is attached to the crankshaft 56 placed between the gasoline engine 50 and a clutch motor 30B. In the power output apparatus 20B of Fig. 26, like elements as those of the power output apparatus 20 of Fig. 1 are shown by like numerals or symbols and are not explained here. The symbols used in the above description have like meanings unless otherwise specified.

The following describes operation of the power output apparatus 20B shown in Fig. 26. By way of example, it is assumed that the gasoline engine 50 is driven with a torque Te and at a revolving speed Ne. When a torque Ta is added to the crankshaft 56 by the assist motor 40B linked with the crankshaft 56, the sum of the torques (Te+Ta) consequently acts on the crankshaft 56. When the clutch motor 30B is controlled to produce the torque Tc equal to the sum of the torques (Te+Ta), the torque Tc (=Te+Ta) is eventually transmitted from the clutch motor 30B to the drive shaft 22.

When the vehicle is driven in a normal driving state, that is, when the revolving speed Nd of the drive shaft 22 is lower than the revolving speed Ne of the gasoline engine 50 (Nd<Ne), the clutch motor 30B regenerates electric power based on the revolving speed difference Nc between the revolving speed Ne of the gasoline engine 50 and the revolving speed Nd of the drive shaft 22. The regenerated power is supplied to the assist motor 40B via the first and the second driving circuits 91 and 92 to activate the assist motor 40B. Provided that the torque Ta of the assist motor 40B is set to a value, which enables the assist motor 40B to consume the electrical energy substantially equivalent to the electrical energy regenerated by the clutch motor 30B, free torque conversion is allowed for the energy output from the gasoline engine 50 within a range holding the relationship of Equation (5) given below. Since the relationship of Equation (5) represents the ideal state with an efficiency of 100%, (Tc×Nd) is a little smaller than (Te×Ne) in the actual state:

$$Te \times Ne = Tc \times Nd \qquad (5)$$

When the vehicle runs, for example, an expressway at a high speed, that is, when the revolving speed Nd of the drive shaft 22 is higher than the revolving speed Ne of the gasoline engine 50 (Nd>Ne), the clutch motor 30B works as a normal motor. The clutch motor 30B accordingly enhances the speed of rotation of the inner rotor 34 relative to the outer rotor 32. Provided that the torque Ta of the assist motor 40B is set to a negative value, which enables the assist motor 40B to regenerate the electrical energy substantially equivalent to the electrical energy consumed by the clutch motor 30B, free torque conversion is also allowed for the energy output from the gasoline engine 50 within a range holding the relationship of Equation (5) given above.

The power output apparatus 20B of this modified structure can also set the vehicle in a free running state as described below.

By way of example, it is assumed that the gasoline engine 50 driven by the EFIECU 70 rotates at a predetermined revolving speed Ne, while the drive shaft 22 is rotated in the direction of rotation of the crankshaft 56 at a predetermined revolving speed Nd. The revolving speed Nd of the drive shaft 22 may be smaller than (corresponding to the normal driving state), greater than (corresponding to the high-speed driving state), or equal to the revolving speed Ne of the crankshaft 56.

In the same manner as the first through the third embodiments described above, the control CPU 90 of the controller 80 of the power output apparatus 20B refers to the output data of the residual capacity meter 99, and determines whether the residual capacity BRM of the battery 94 is less than the allowable minimum value Bmin or greater than the allowable maximum value Bmax to be out of the allowable range or alternatively not less than the allowable minimum value Bmin and not greater than the allowable maximum value Bmax to be within the allowable range.

When the residual capacity BRM of the battery 94 is smaller than the allowable minimum value Bmin and thus det rmined to be out of the allowable range, the control CPU 90 controls the first driving circuit 91 to prevent an electric current from flowing through the three-phase coils 36 of the clutch motor 30B. This substantially disconnects the electromagnetic coupling of the outer rotor 32 with the inner rotor 34 in the clutch motor 30B. The drive shaft 22 is thus com-

mounted thereon. In this structure, the outer rotor 32D of the clutch motor 30D also works as a rotor of the assist motor 40D.

In the power output apparatus 20D, the voltage applied to the three-phase coils 36 on the inner rotor 34 is controlled against the inner-surface magnetic pole of the permanent magnets 35D set on the outer rotor 32D. This allows the clutch motor 30D to work in the same manner as the clutch motor 30B of the power output apparatus 20B shown in Fig. 26. The voltage applied to the three-phase coils 44 on the stator 43 is controlled against the outer-surface magnetic pole of the permanent magnets 35D set on the outer rotor 32D. This allows the assist motor 40D to work in the same manner as the assist motor 40B of the power output apparatus 20B. The control procedures of the first through the third embodiments discussed above are also applicable to the power output apparatus 20D shown in Fig. 30, which accordingly exerts the same effects as those of the power output apparatus 20B shown in Fig. 26.

Like the power output apparatus 20A of Fig. 25, in the power output apparatus 20D of Fig. 30, the clutch motor 30D and the assist motor 40D are integrally joined with each other, which shortens the length of the power output apparatus 20D along the drive shaft 22. The outer rotor 32D functions concurrently as one of the rotors in the clutch motor 30D and as the rotor of the assist motor 40D, thereby effectively reducing the size and weight of the whole power output apparatus 20D.

In all the structures of Figs. 1, 25, 26, 29, and 30, the power output apparatus includes the assist motor 40 as well as the clutch motor 30. The free running state of the vehicle may, however, be realized by the structure of Fig. 1 without the assist motor 40. In this modified structure without the assist motor 40, when no electric current is made to flow through the three-phase coils 36 of the clutch motor 30, the electromagnetic coupling of the outer rotor 32 with the inner rotor 34 is substantially disconnected in the clutch motor 30. The drive shaft 22 is thus completely disconnected and free from the crankshaft 56. The clutch motor 30 accordingly does not apply any torque to the drive shaft 22. This makes the output torque Td of the drive shaft 22 substantially equal to zero, thereby realizing a free running state of the vehicle. In this case, the gasoline engine 50 may be stopped or kept at an idle.

In the embodiments discussed above, when the residual capacity BRM of the battery 94 is within the allowable range, the power output apparatus is set into the third arrangement of operation, in which both the clutch motor 30 and the assist motor 40 are controlled to stop operation and the battery 94 is kept in the current state without any supplement or consumption of electric power. As long as the residual capacity BRM of the battery 94 is kept within the allowable range, the clutch motor 30 or the assist motor 40 may be controlled to implement either the power operation or the regenerative operation to consume or supplement the electric power of the battery 94. In the second, fifth, or seventh arrangement of operation, the gasoline engine 50 is controlled to exert an effect of engine brake. A braking mechanism, such as a mechanical brake, may, however, be used in place of the gasoline engine 50.

In the above embodiments, no auxiliary machines (for example, a cooling a pump, a power steering pump, and a compressor for an air conditioner) or other torque-producing machines are connected with the crankshaft 56 or the drive shaft 22. When any torque-producing machine is attached to the crankshaft 56 or the drive shaft 22, it is required to control the gasoline engine 50, the clutch motor 30, and the assist motor 40 by taking into account the torques applied from the torque-producing machine to the crankshaft 56 and the drive shaft 22, in order to make the torque output to the drive shaft 22 substantially equal to zero.

In the above embodiments, the electric power regenerated by the clutch motor 30 or the assist motor 40 is stored into the battery 94. In accordance with one preferred structure, the regenerated electric power is not stored into the battery 94 but is consumed by a variety of electrical equipment (for example, lighting facilities, sound facilities, and cooling facilities) mounted on the vehicle. In accordance with another preferred structure, the regenerated electric power is partly stored into the battery 94 while the remaining part being consumed by a variety of electrical equipment. In the embodiments discussed above, one or both of the clutch motor 30 and the assist motor 40 carry out the power operation with either or both of the electric power supplied from the battery 94 and the electric power regenerated by the other motor. Electric power generated by another generator means may, however, be used for the power operation.

In the above embodiments, the outer rotor 32 of the clutch motor 30 is directly linked with the crankshaft 56, the inner rotor 34 of the clutch motor 30 with the drive shaft 22, and the rotor 42 of the assist motor 40 with either the drive shaft 22 or the crankshaft 56. The connection may, however, be attained via any coupling means, such as a gear or a belt.

The gasoline engine 50 driven by means of gasoline is used as the engine in the above embodiments. The principle of the invention is, however, applicable to other internal combustion engines and external combustion engines, such as Diesel engines, turbine engines, and jet engines.

Permanent magnet (PM)-type synchronous motors are used for the clutch motor 30 and the assist motor 40 in the power output apparatuses described above. Other motors such as variable reluctance (VR)-type synchronous motors, vernier motors, d.c. motors, induction motors, and superconducting motors may be used for both the regenerative operation and power operation, while stepping motors are applicable only for the power operation.

In the above embodiments discussed above, the outer rotor 32 of the clutch motor 30 is linked with the crankshaft 56, whereas the inner rotor 34 is connected to the drive shaft 22. Alternatively, the outer rotor 32 may be linked with the

5. A power output apparatus in accordance with claim 2, wherein said third rotor is mounted on said second rotor connected with said drive shaft.

6. A power output apparatus in accordance with claim 1, said power output apparatus further comprising:

storage means for storing electric power; and wherein

said control means comprises means for controlling said first motor-driving means to supply the electric power stored in said storage means to said first motor in order to activate said first motor, and controlling said second motor-driving means to supply the electric power stored in said storage means to said second motor in order to activate said second motor.

7. A power output apparatus in accordance with claim 6, said power output apparatus further comprising:

residual capacity measuring means for measuring a residual capacity of electric power stored in said storage means; and

means for enabling said control means to carry out said control of said first and second motor-driving means when the residual capacity measured by said residual capacity measuring means is greater than a predetermined value.

8. A power output apparatus in accordance with claim 6, wherein said third rotor is mounted on said second rotor connected with said drive shaft.

9. A power output apparatus in accordance with claim 1, wherein

said control means comprises means for controlling said second motor-driving means to enable said second motor to regenerate electric power, and controlling said first motor-driving means to supply the regenerated electric power to said first motor in order to activate said first motor.

10. A power output apparatus in accordance with claim 9, said power output apparatus further comprising:

storage means for storing electric power; and wherein

said control means further comprises means for storing at least part of the regenerated electric power into said storage means.

11. A power output apparatus in accordance with claim 10, said power output apparatus further comprising:

residual capacity measuring means for measuring a residual capacity of electric power stored in said storage means; and

means for enabling said control means to carry out said control of said first and second motor-driving means when the residual capacity measured by said residual capacity measuring means is less than a predetermined value.

12. A power output apparatus in accordance with claim 9, wherein said third rotor is mounted on said second rotor connected with said drive shaft.

13. A power output apparatus in accordance with claim 1, said power output apparatus further comprising:

storage means for storing electric power; and wherein

said control means comprises means for controlling said first motor-driving means to enable said first motor to regenerate electric power, and controlling said second motor-driving means to supply the regenerated electric power and th electric power stored in said storage means to said second motor in order to activate said second motor.

14. A power output apparatus in accordance with claim 13, said power output apparatus further comprising:

said output shaft of said engine and said drive shaft via the electromagnetic coupling of said first and second rotors;

first motor-driving means for exchanging electric currents with said first motor to vary the electromagnetic coupling of said first rotor with said second rotor;

a second motor comprising a stator and a third rotor connected with said drive shaft, said stator being electromagnetically coupled with said third rotor;

second motor-driving means for exchanging electric currents with said second motor to vary the electromagnetic coupling of said stator with said third rotor;

storage means for storing electric power; and

control means for controlling said first motor-driving means to electromagnetically lock up said first rotor relative to said second rotor of said first motor and thereby allow said output shaft of said engine to rotate with said drive shaft in a substantially integral manner, and controlling said second motor-driving means to supply the electric power stored in said storage means to said second motor in order to activate said second motor and thereby make said second motor apply a torque to said drive shaft.

21. A power output apparatus in accordance with claim 20, wherein said third rotor is mounted on said second rotor connected with said drive shaft.

22. A power output apparatus for outputting power to a drive shaft, said power output apparatus comprising:

an engine having an output shaft;

a first motor comprising a first rotor connected with said output shaft of said engine and a second rotor connected with said drive shaft, said second rotor being coaxial to and rotatable relative to said first rotor, said first and second rotors being electromagnetically coupled with each other, whereby power is transmitted between said output shaft of said engine and said drive shaft via the electromagnetic coupling of said first and second rotors;

first motor-driving means for exchanging electric currents with said first motor to vary the electromagnetic coupling of said first rotor with said second rotor;

a second motor comprising a stator and a third rotor connected with said output shaft of said engine, said stator being electromagnetically coupled with said third rotor;

second motor-driving means for exchanging electric currents with said second motor to vary the electromagnetic coupling of said stator with said third rotor; and

control means for controlling said first motor-driving means to substantially disconnect the electromagnetic coupling of said first rotor with said second rotor in said first motor, and controlling said second motor-driving means to enable said second motor to regenerate electric power.

23. A power output apparatus in accordance with claim 22, said power output apparatus further comprising:

storage means for storing electric power; and wherein

said control means further comprises means for storing at least part of the regenerated electric power into said storage means.

24. A power output apparatus in accordance with claim 23, said power output apparatus further comprising:

residual capacity measuring means for measuring a residual capacity of electric power stored in said storage means; and

driving condition detecting means for detecting a driving condition of said transportation system; and

control means for, when the driving condition detected by said driving condition detecting means represents a predetermined state, controlling said engine, said first motor, and said second motor to make a torque output to said drive shaft approximately equal to zero.

30. A power output apparatus for outputting mechanical energy as power to a drive shaft, said power output apparatus comprising:

an engine connected with a rotating shaft;

a first motor connected with said rotating shaft; and

a second motor connected with said drive shaft;

wherein said engine produces mechanical energy and transmits the mechanical energy to said rotating shaft;

said first motor converts part of the mechanical energy transmitted via said rotating shaft to electrical energy while transmits the residual mechanical energy to said second motor; and

said second motor converts the mechanical energy transmitted from said first motor to electrical energy without transmitting any mechanical energy to said drive shaft.

31. A power output apparatus in accordance with claim 30, said power output apparatus further comprising:

storage means for storing at least part of the electrical energy converted from the mechanical energy.

32. A power output apparatus for outputting mechanical energy as power to a drive shaft, said power output apparatus comprising:

an engine connected with a rotating shaft;

a first motor connected with said rotating shaft;

a second motor connected with said drive shaft; and

storage means for storing electrical energy;

wherein said first motor converts the electrical energy supplied from said storage means to mechanical energy and transmits the sum of the mechanical energy converted from the electrical energy and mechanical energy transmitted from a second motor to said rotating shaft;

said second motor converts the electrical energy supplied from said storage means to mechanical energy and transmits the mechanical energy to said first motor without transmitting any mechanical energy to said drive shaft; and

said engine converts the mechanical energy transmitted via said rotating shaft to another form of energy.

33. A power output apparatus for outputting mechanical energy as power to a drive shaft, said power output apparatus comprising:

an engine connected with a rotating shaft;

a first motor connected with said rotating shaft; and

a second motor connected with said drive shaft;

(b-3) storing at least part of the regenerated electric power into said storage means.

38. A method in accordance with claim 36, wherein

said step (a) comprises the step of providing storage means for storing electric power; and

said step (b) comprises the steps of:

(b-1) supplying the electric power stored in said storage means to said first motor in order to activate said first motor; and

(b-2) supplying the electric power stored in said storage means to said second motor in order to activate said second motor.

39. A method in accordance with claim 36, wherein

said step (a) comprises the step of providing storage means for storing electric power; and

said step (b) comprises the steps of:

(b-1) enabling said second motor to regenerate electric power;

(b-2) supplying the regenerated electric power to said first motor in order to activate said first motor; and

(b-3) storing at least part of the regenerated electric power into said storage means.

40. A method in accordance with claim 36, wherein

said step (a) comprises the step of providing storage means for storing electric power; and

said step (b) comprises the steps of:

(b-1) enabling said first motor to regenerate electric power; and

(b-2) supplying the regenerated electric power and the electric power stored in said storage means to said second motor in order to activate said second motor.

Fig. 2

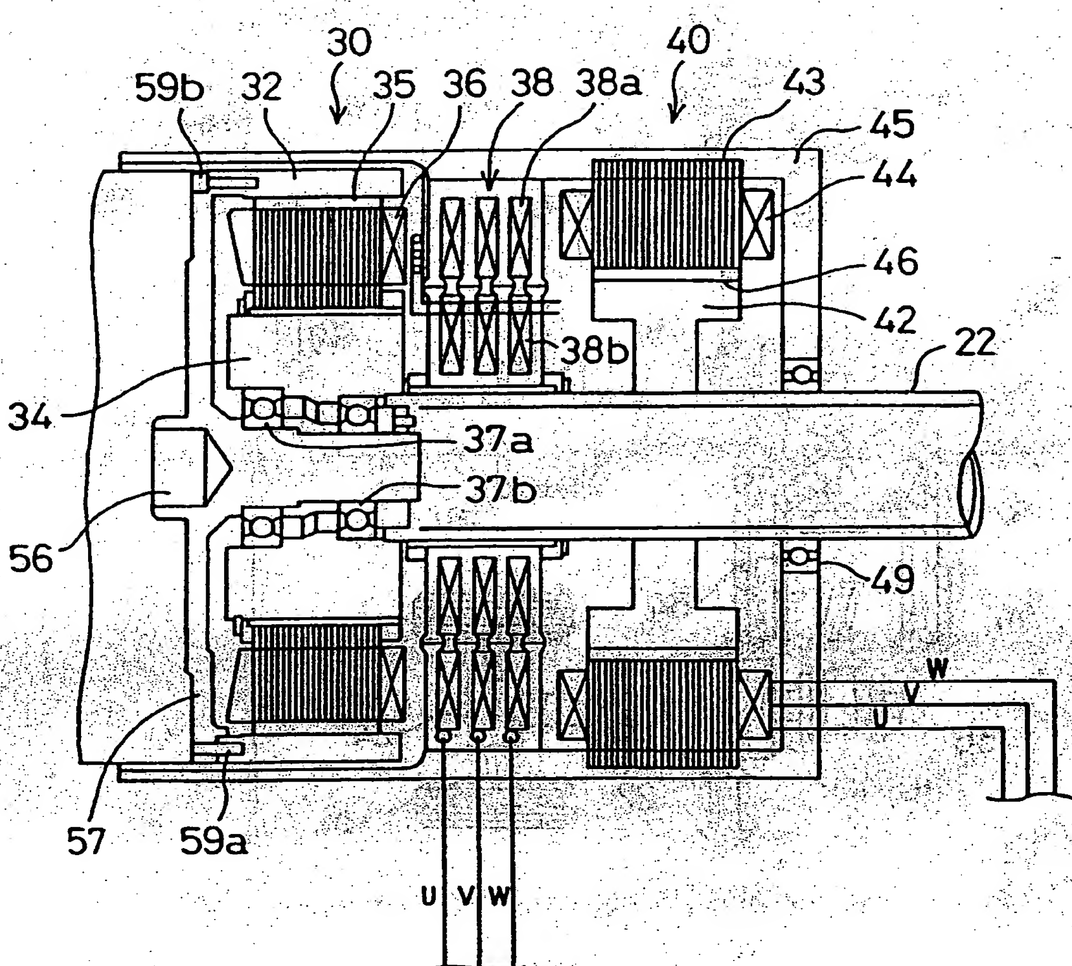

30
40
59b
32
35
36
38
38a
43
45
44
46
42
22
38b
34
37a
37b
56
49
W
V
U
57
59a
U V W

Fig. 4

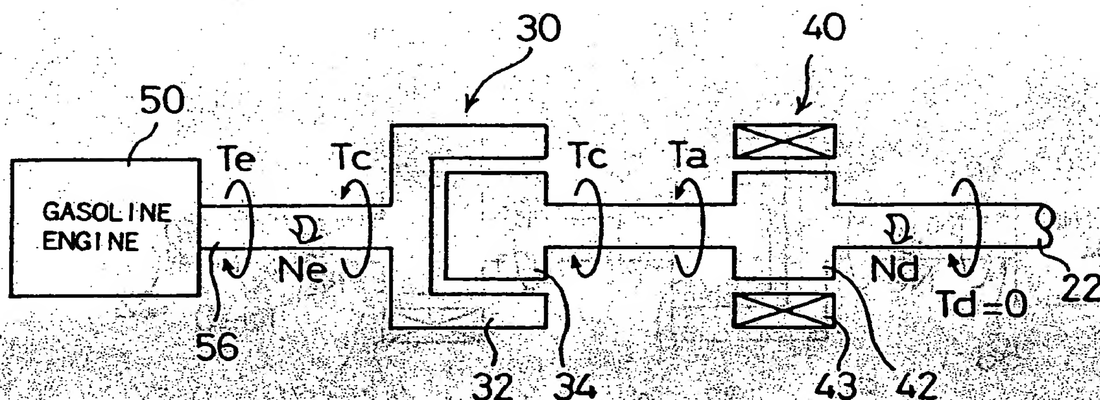


Fig. 6

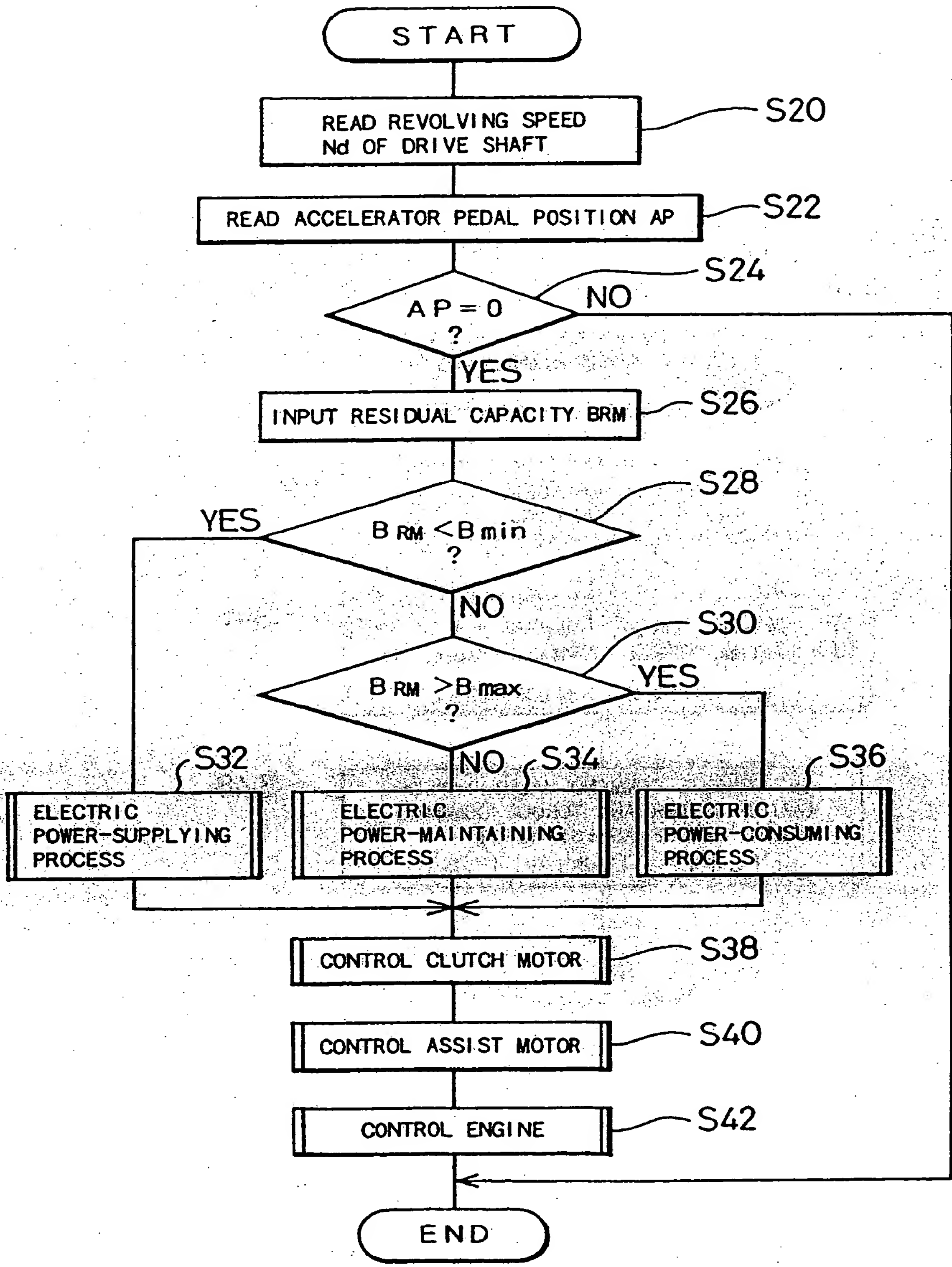

START
READ REVOLVING SPEED Nd OF DRIVE SHAFT
S20
READ ACCELERATOR PEDAL POSITION AP
S22
AP = 0 ?
S24
NO
YES
INPUT RESIDUAL CAPACITY BRM
S26
B RM <B min ?
S28
YES
NO
B RM >B max ?
S30
YES
NO
S32
ELECTRIC POWER-SUPPLYING PROCESS
S34
ELECTRIC POWER-MAINTAINING PROCESS
S36
ELECTRIC POWER-CONSUMING PROCESS
CONTROL CLUTCH MOTOR
S38
CONTROL ASSIST MOTOR
S40
CONTROL ENGINE
S42
END

Fig. 8

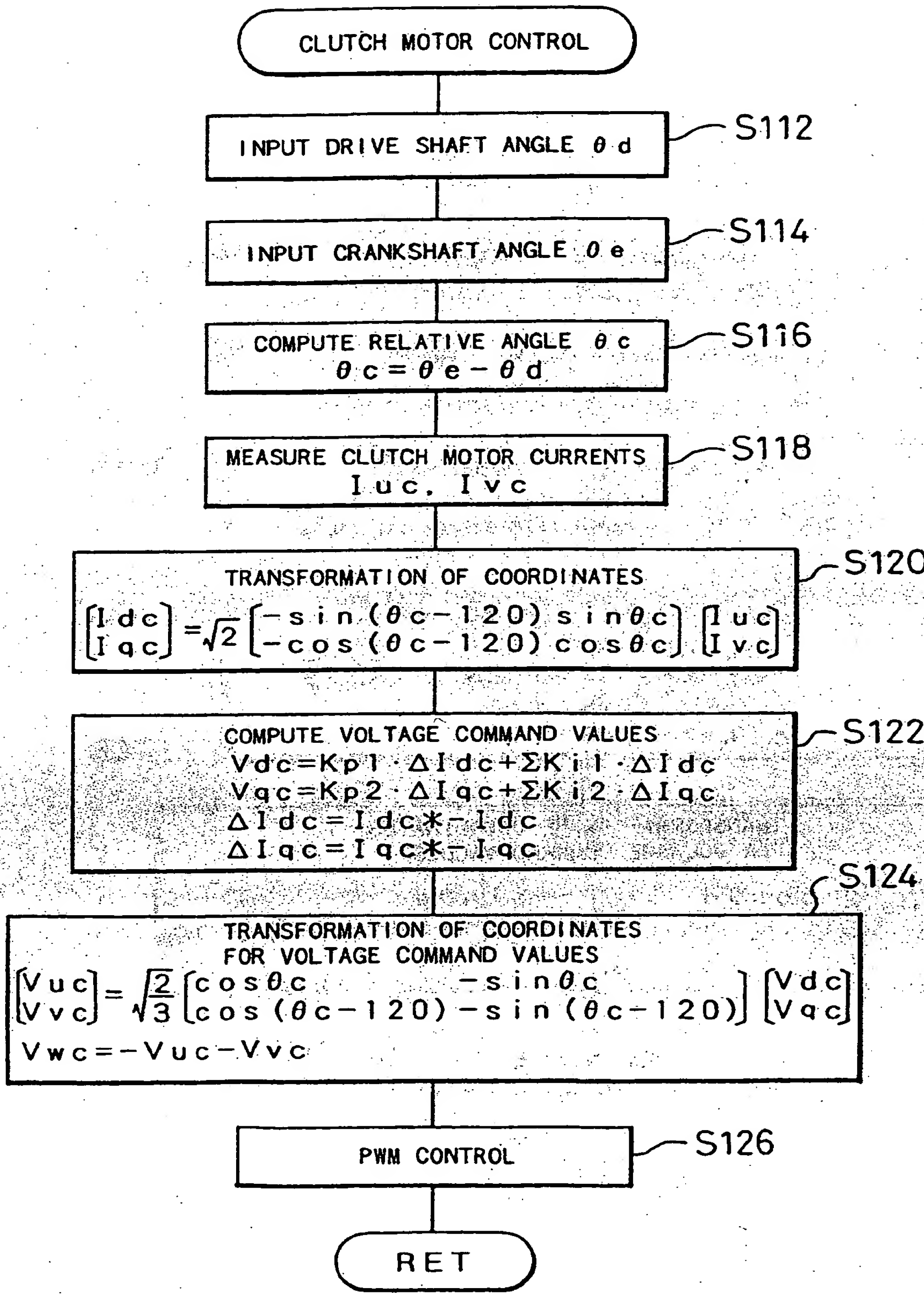

CLUTCH MOTOR CONTROL
INPUT DRIVE SHAFT ANGLE θd
S112
INPUT CRANKSHAFT ANGLE θe
S114
COMPUTE RELATIVE ANGLE θc
θc = θe − θd
S116
MEASURE CLUTCH MOTOR CURRENTS
Iuc, Ivc
S118
TRANSFORMATION OF COORDINATES
[Idc; Iqc] = √2 [−sin(θc−120) sinθc; −cos(θc−120) cosθc] [Iuc; Ivc]
S120
COMPUTE VOLTAGE COMMAND VALUES
Vdc=Kp1·ΔIdc+ΣKi1·ΔIdc
Vqc=Kp2·ΔIqc+ΣKi2·ΔIqc
ΔIdc=Idc*−Idc
ΔIqc=Iqc*−Iqc
S122
TRANSFORMATION OF COORDINATES
FOR VOLTAGE COMMAND VALUES
[Vuc; Vvc] = √(2/3) [cosθc −sinθc; cos(θc−120) −sin(θc−120)] [Vdc; Vqc]
Vwc=−Vuc−Vvc
S124
PWM CONTROL
S126
RET

Fig. 10

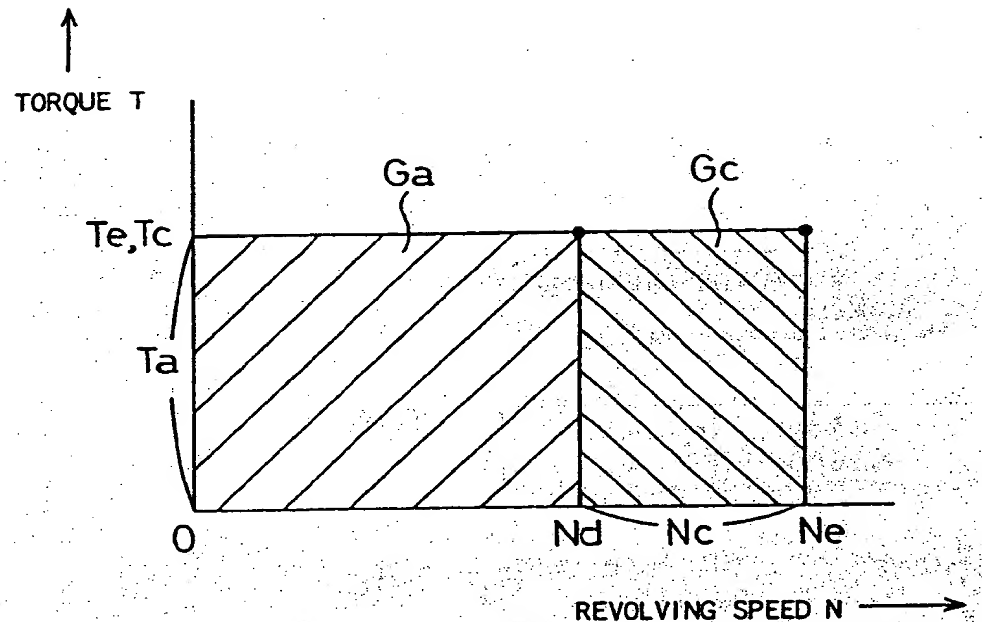

TORQUE T
Ga
Gc
Te,Tc
Ta
0
Nd
Nc
Ne
REVOLVING SPEED N

Fig. 11

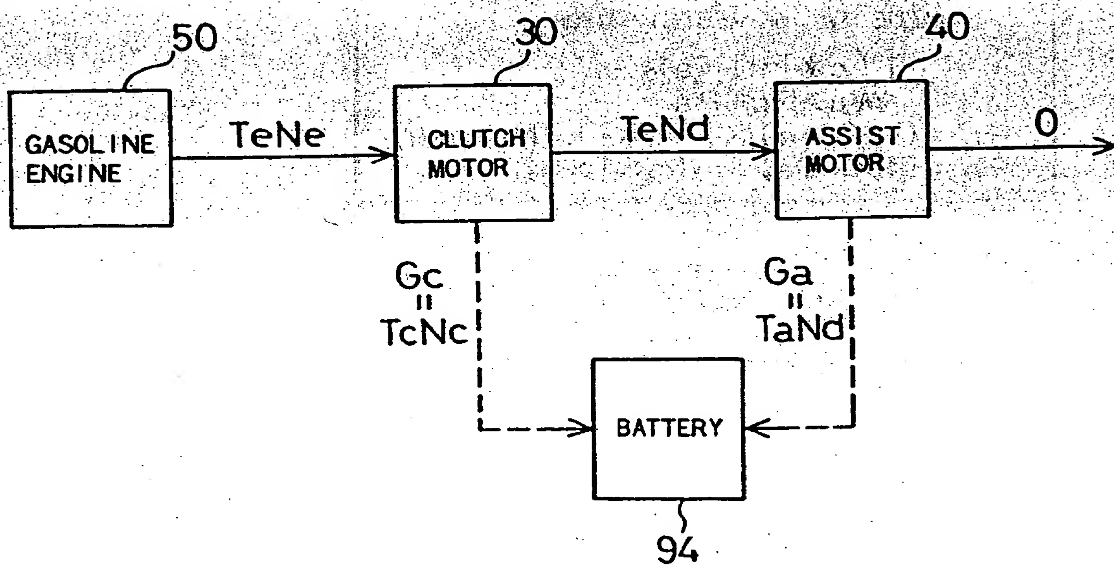

50
30
40
GASOLINE ENGINE
TeNe
CLUTCH MOTOR
TeNd
ASSIST MOTOR
0
Gc = TcNc
Ga = TaNd
BATTERY
94

Fig. 13

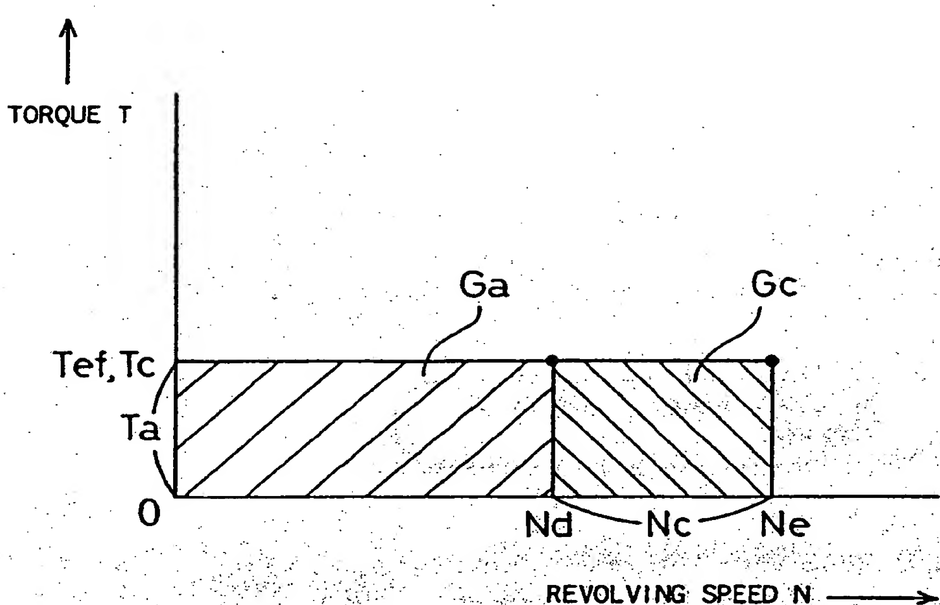

TORQUE T
Ga
Gc
Tef, Tc
Ta
0
Nd
Nc
Ne
REVOLVING SPEED N

Fig. 14

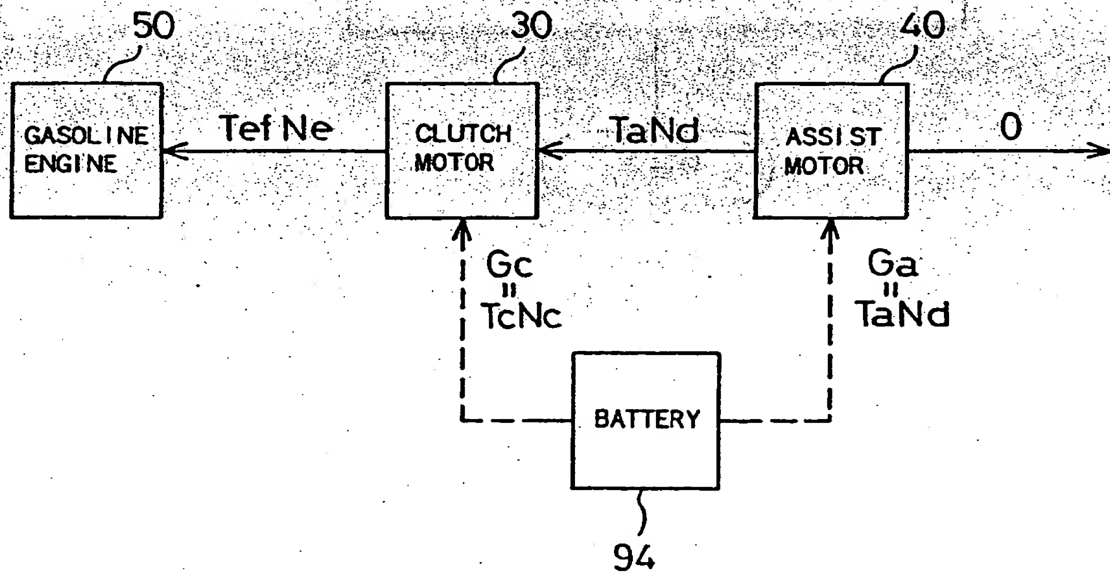

50
30
40
GASOLINE ENGINE
Tef Ne
CLUTCH MOTOR
TaNd
ASSIST MOTOR
0
Gc = TcNc
Ga = TaNd
BATTERY
94

Fig. 16

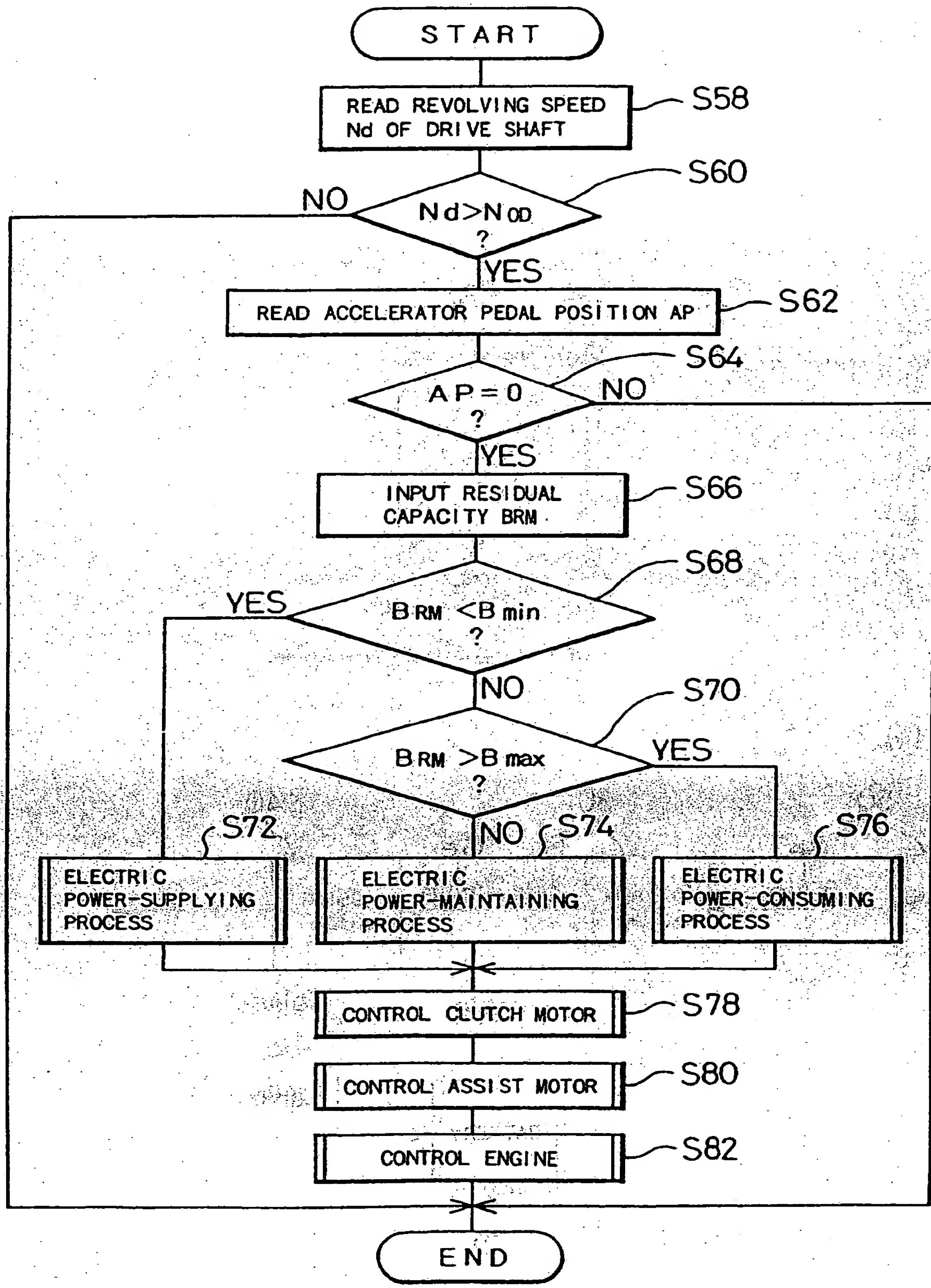

START
READ REVOLVING SPEED Nd OF DRIVE SHAFT
S58
Nd>NOD ?
S60
NO
YES
READ ACCELERATOR PEDAL POSITION AP
S62
AP=0 ?
S64
NO
YES
INPUT RESIDUAL CAPACITY BRM
S66
BRM <B min ?
S68
YES
NO
BRM >B max ?
S70
YES
NO
S72
ELECTRIC POWER-SUPPLYING PROCESS
S74
ELECTRIC POWER-MAINTAINING PROCESS
S76
ELECTRIC POWER-CONSUMING PROCESS
CONTROL CLUTCH MOTOR
S78
CONTROL ASSIST MOTOR
S80
CONTROL ENGINE
S82
END

Fig. 19

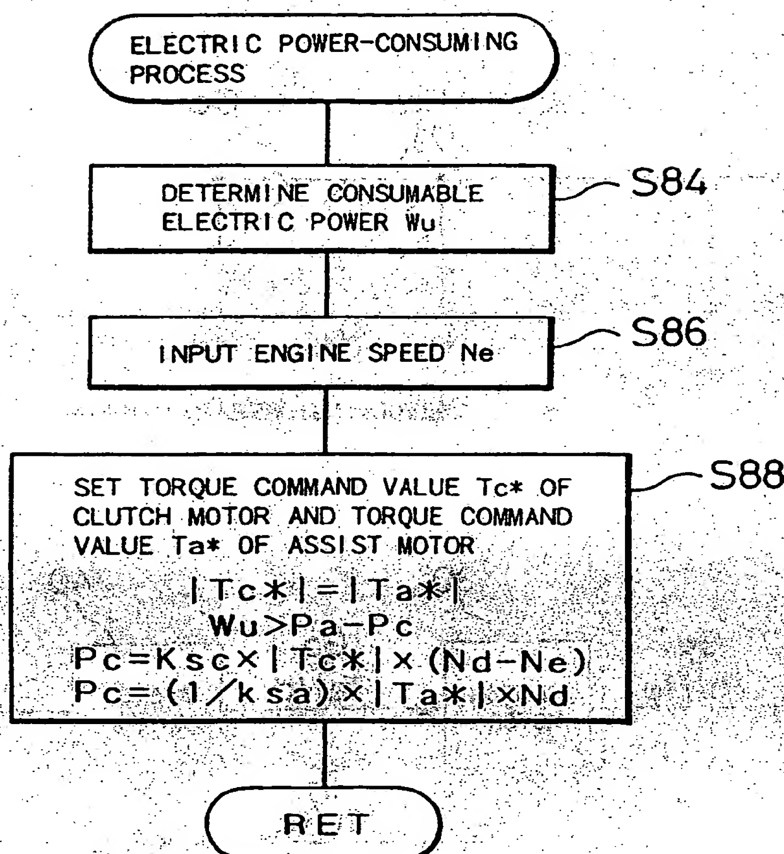

ELECTRIC POWER-CONSUMING PROCESS
DETERMINE CONSUMABLE ELECTRIC POWER Wu
S84
INPUT ENGINE SPEED Ne
S86
SET TORQUE COMMAND VALUE Tc* OF CLUTCH MOTOR AND TORQUE COMMAND VALUE Ta* OF ASSIST MOTOR
|Tc*|=|Ta*|
Wu>Pa−Pc
Pc=Ksc×|Tc*|×(Nd−Ne)
Pc=(1/ksa)×|Ta*|×Nd
S88
RET

Fig. 22

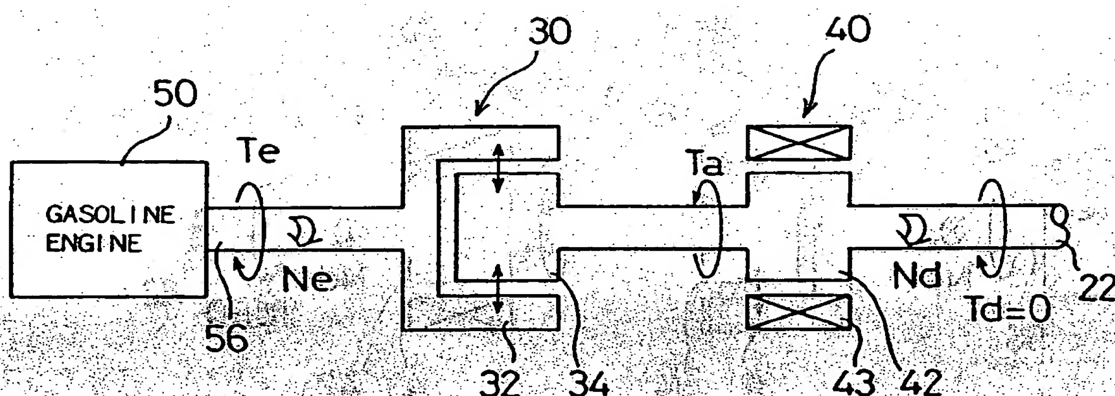


Fig. 24

RELATIONS OF REVOLVING SPEEDS	RESIDUAL CAPACITY OF BATTERY	ARRANGEMENT OF OPERATION	GASOLINE ENGINE	CLUTCH MOTOR	ASSIST MOTOR
NORMAL DRIVING STATE $Ne > Nd$	INSUFFICIENT $B_{RM} < B_{min}$	1	DRIVING OPERATION	REGENERATIVE OPERATION	REGENERATIVE OPERATION
	EXCESS $B_{RM} > B_{max}$	2	BRAKING OPERATION (ENGINE BRAKE)	POWER OPERATION	POWER OPERATION
HIGH-SPEED DRIVING STATE (OVERDRIVE STATE) $Ne < Nd$	INSUFFICIENT $B_{RM} < B_{min}$	4	DRIVING OPERATION	POWER OPERATION	REGENERATIVE OPERATION
	EXCESS $B_{RM} > B_{max}$	5	BRAKING OPERATION (ENGINE BRAKE)	REGENERATIVE OPERATION	POWER OPERATION
$Ne = Nd$	INSUFFICIENT $B_{RM} < B_{min}$	6	DRIVING OPERATION	LOCK-UP STATE	REGENERATIVE OPERATION
	EXCESS $B_{RM} > B_{max}$	7	BRAKING OPERATION (ENGINE BRAKE)	LOCK-UP STATE	POWER OPERATION
―	APPROPRIATE $B_{min} \leq B_{RM} \leq B_{max}$	3	STOP WORKING OR IDLING STATE	STOP WORKING	STOP WORKING

Fig. 27

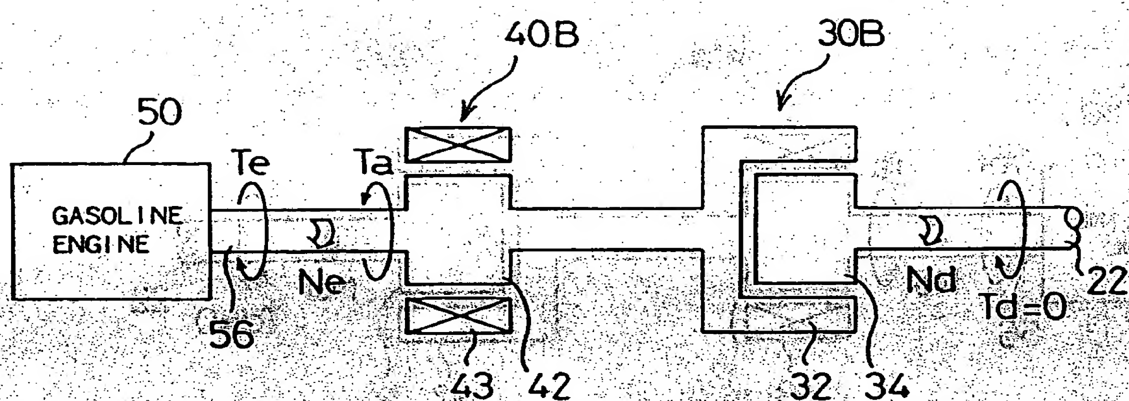


Fig. 29

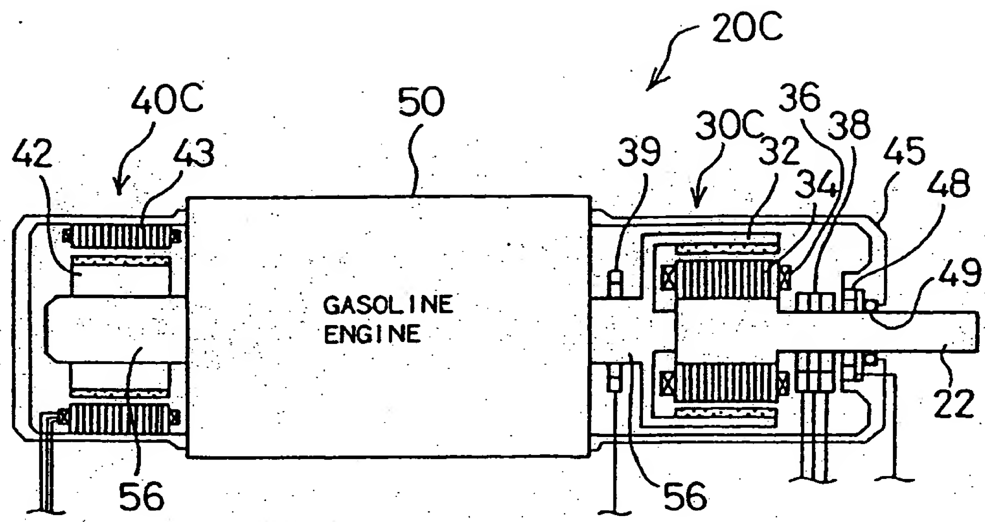
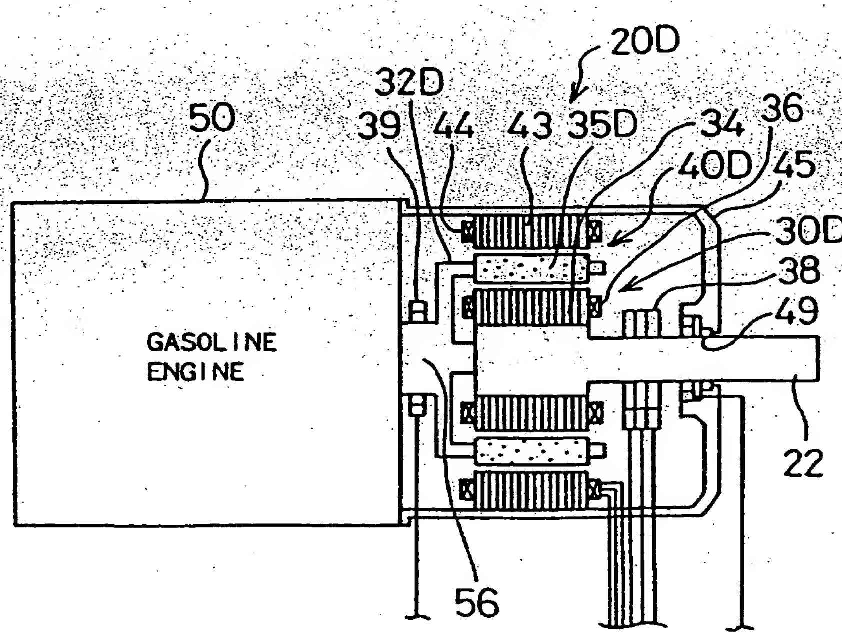

20C
40C
50
36
30C
38
42
43
39
32
45
34
48
GASOLINE
ENGINE
49
22
56
56

Fig. 30


20D
32D
50
39
44
43
35D
34
36
40D
45
30D
38
49
GASOLINE
ENGINE
22
56

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(71) Applicant:
**TOYOTA JIDOSHA KABUSHIKI KAISHA
Aichi-ken 471 (JP)**

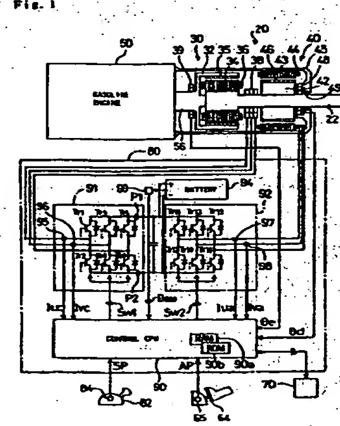
(72) Inventors:
- **Yamada, Eiji,
c/o Toyota Jidosha K.K.
Toyota-shi, Aichi-ken, 471 (JP)**
- **Miyatani, Takao
c/o Toyota Jidosha K.K.
Toyota-shi, Aichi-ken, 471 (JP)**
- **Kawabata, Yasutomo,
c/o Toyota Jidosha K.K.
Toyota-shi, Aichi-ken, 471 (JP)**
- **Kanamori, Akihiko,
c/o Toyota Jidosha K.K.
Toyota-shi, Aichi-ken, 471 (JP)**

(74) Representative:
**KUHNEN, WACKER & PARTNER
Alois-Steinecker-Strasse 22
85354 Freising (DE)**

(54) **Hybrid vehicle power output apparatus and method of controlling the same**

(57) A power output apparatus (20) of the present invention includes a clutch motor (30), an assist motor (40), and a controller (80) for controlling the clutch motor (30) and the assist motor (40). The clutch motor (30) includes an outer rotor (32) linked with a crankshaft (56) of a gasoline engine (50) and an inner rotor (34) connecting with a drive shaft (22). The assist motor (40) includes a rotor (42) connecting with the drive shaft (22). When the residual capacity of a battery (94) is less than an allowable minimum value, a control CPU (90) of the controller (80) controls a first driving circuit (91) to enable the clutch motor (30) to carry out the power operation and apply a first torque to the drive shaft (22) in the direction of rotation of the drive shaft (22). The control CPU (90) concurrently controls a second driving circuit (92) to enable the assist motor (40) to carry out the regenerative operation and apply a second torque to the drive shaft (22) in the reverse of the rotation of the drive shaft (22). The second torqu is substantially equal in magnitude but opposite in direction to the first torque. The electric power regenerated by the assist motor (40) is supplied to the battery (94) to supplement the electric power of the battery (94). The power output apparatus (20) of the invention can thus make the torque output to the drive shaft (22) approximately equal to zero.

Fig. 1



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